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TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION

OCTOBER 1977

Phase 2

FINAL REPORT

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16. Abstract

A particulate sampling system has been designed and fabricated for the collection of exhaust particles emitted by aircraft turbine engines. The samples obtained by the sampling system were suitable for the determination of total mass emission rate and characterization of the exhaust particles. Two separate samples were necessary - a bulk sample for mass emission rate and a light deposit of particles for individual characterization.

Operational adjustments and performance evaluations were made utilizing a TF-30 mixed-flow turbojet engine. The reliability of the data was established through repeated tests and the collaboration among the different techniques used to characterize the particles.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	*centimeters*	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	*hectares*	*ha*
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	*teaspoons*	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	*l*
gal	gallons	3.8	liters	l
ft^3	cubic feet	*0.03*	*cubic meters*	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	*yards*	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	*kilograms*	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	*pints*	pt
l	liters	1.06	quarts	qt
l	*liters*	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

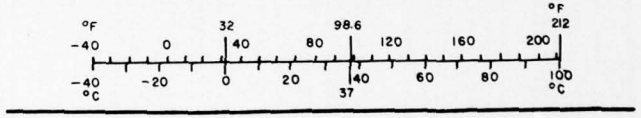
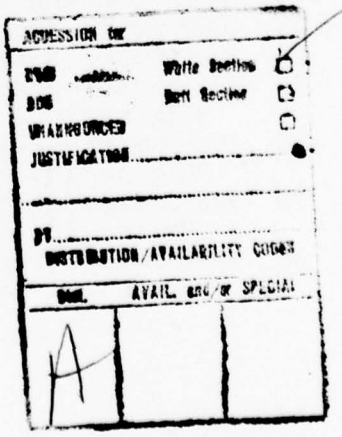


TABLE OF CONTENTS



LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION

1. INTRODUCTION

A particulate sampling system for aircraft engine exhaust particles has been designed and constructed. The particle information obtainable from the sampling system includes: mass concentration, particle size distribution, particle morphology, and the variation of particle shape with size. The performance of the system has been evaluated twice through actual engine tests at the Federal Aviation Administrations' test facility - National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey.

This program is composed of three separately funded phases, the second of which is this final report. The first phase consisted of a literature review and the establishment of design guidelines for the sampling system. The second phase was concerned with carrying through these guidelines to a properly evaluated working sampling system. The third and last phase will include the collecting of data from JT-8D and JT-9D engines. Analysis of the resultant data will consist of determination of particulate mass emission rates and particle analysis pertinent to engine operating condition, fuel, and combustion relationships. Additionally, environmental and economic impacts of the particulate emissions are to be assessed.

Results of the first phase indicated that the point of particle collection should be as near the engine as practical to avoid particle deposition which could alter the sample extracted from the engine. The flow requirements were established and system components selected for use.

The sampling system constructed under Phase 2 extracts a sample from the exit plane of the engine for collection on a suitable substrate. The sampling probe assembly is composed of four nozzles evenly spaced on an arc whose radius is 62% of the engine's exit plane radius. This geometry corresponds

to the FAA's recommended methodology for gaseous emission sampling. The extracted sample is then transported, avoiding particle deposition over much of the tube length to the point of particle collection. In this manner, the sample is simultaneously diluted, cooled, and conditioned to minimize local condensation and any sample bias. After conditioning, the sample is bifurcated - the larger portion of which is collected in bulk and the lesser portion deposited on special substrates for individual particle analysis. The substrate used for the bulk particulate sample is the glass fiber filter. Carbon-coated electron microscope grids in conjunction with Nuclepore membrane filters serve as substrates for particle analysis.

Two separate sampling tests were conducted at the FAA's NAFEC test center utilizing the JT-30 turbofan engine. The objective of these tests was to provide opportunity to perform final adjustment of the system's operation and the evaluation of overall results. Numerous samples were obtained and analyzed in a manner identical to that planned for the operational tests. The reliability of the data was substantiated by the collaboration of the particle size results and special tests indicating repeatability of the sampling procedure.

The report is composed of two major parts. Section 2 presents and discusses details concerning the design of the sampling system hardware. The operating procedures developed during engine sampling at NAFEC are also discussed. Section 3 presents the sampling results and develops the conclusions located at the end of the report.

2. DESIGN AND OPERATION OF SAMPLING SYSTEM

Two fundamental requirements were met in the design of the sampling system. First, the particulate samples collected must represent accurately the conditions at the exit plane of the engine throughout the sampling system. The sample volume extracted from the engine must pass through the sampling system in such a way that the sample does not change its characteristics.

Second, the sampling system must achieve this goal with minimum cost resulting both from the fabrication of the sampling system itself and the required engine operation time necessary for sample acquisition.

Within this section of the report, both the design philosophy and designed hardware are discussed. The discussion is broken down into two parts: the overall system flow geometry and the system's hardware.

2.1 System Flow Design

The system flow design was governed by the following factors:

- methodology required to minimize particulate deposition,
- flow rates required to yield adequate samples within reasonable time intervals, and
- isokinetic sampling conditions maintained to avoid sample bias.*

Deposition was considered so important that the entire collection system was placed as near to the engine as practical. This reduced transport length of the particulate sample. The sample flow rates were based on current engine particulate mass emission rates because a weighable sample was necessary for mass emission data.

To achieve the shortest tube length and minimum deposition, the bulk of the transport length was purged with dilution air to prevent collected particles from coming in contact with the wall and thus being removed from the moving sample stream. This increased the flow through the collection system and therefore posed an upper bound on the sample flow rate extractable from the engine maintaining a specific dilution air/sample flow ratio. Moreover, the dilution air served as a "conditioner" for

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* See Phase I report, page 29.

the extracted sample. The temperature of the sample flow was cooled continuously over the length and the dew point reduced avoiding local condensation.*

Figure 1 is a schematic diagram showing the components of the sampling system and Table 1 lists the specifications pertinent to the sampling system. The diluter was that transport tube length purged with clean dilution air. To follow through the entire system, the engine exhaust sample first entered the sampling probe assembly mounted in close proximity to the engine's exit plane (within 2 in.). The four independent sample tubes on the probe assembly were manifolded to a 3/4" I.D. flexible couplings, permitting movement of the engine. Next, the sample flow was diluted and cooled through the diluter and then passed through a 2 in. line to where the bulk of the particulate material was captured for gravimetric analysis. A glass fiber filter was used as the filtration media. Prior to the mass-sampling turret, a secondary flow of diluted sample was extracted through a small diameter tube to generate samples suitable for microscopic analysis and for use with the Electrical Aerosol Analyzer (EAA). Downstream from the particle collection stations, the sample flow was measured and handled in a manner allowing the appropriate conditions for sampler operation.

The sample flow was necessarily bifurcated to acquire the extremely light loading of the particles important for microscopic analysis. If the particles are too dense on the collection substrate, individual particles are difficult to distinguish; while on the other hand, too sparse a loading results in extended analysis time and possible statistical problems in characterizing the particles. The secondary diluter aided this problem through further dilution - flow rate was from 0.2 to 1.0 scfm.

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* See Phase I report, page 60.

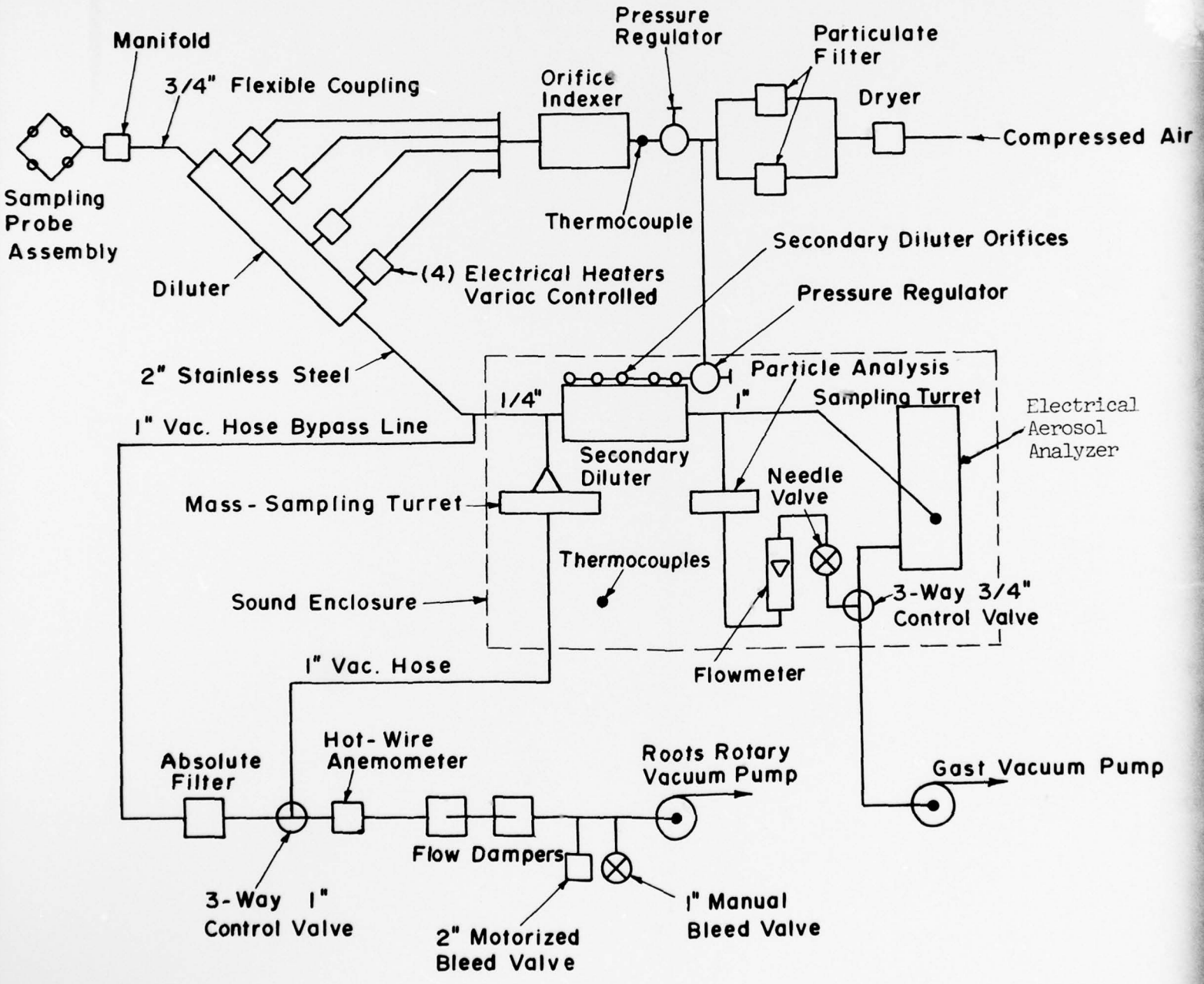


Figure 1

SCHEMATIC DIAGRAM OF THE ENGINE EXHAUST PARTICULATE SAMPLER

Table 1

SPECIFICATIONS FOR SAMPLING SYSTEM

1. Sampling Probe Assembly* - NAFEC Diamond Configuration
   (a) number of nozzles, 4 center located
   (b) nozzle diameter, 0.059 in ± 0.001
   (c) nozzle material, CRES 304
   (d) tubing, 3/8" x 16" stainless steel
   (e) support frame, mild steel
   (f) Manifold assembly, combines four independent sample lines
   (g) sample flow range, 0.5-2.8 scfm

2. Flexible Joint
   (a) length, 3'
   (b) nominal inside diameter, 1"
   (c) liner, 0.004 spot-welded stainless steel

3. Diluter
   (a) length, 72"
   (b) porous tube diameter (inside), 2"
   (c) outer tube (manifold) diameter, 4"
   (d) inlet nominal diameter, 1"
   (e) outlet nominal diameter, 2"
   (f) porous tube material, sintered stainless steel - 2μm pore size
   (g) manifold tube, aluminum - 1/4" wall
   (h) number clean-air inlets, 4 (1/2" diameter)
   (i) insulation, foam rubber secured with duct tape
   (j) clean air heaters, 4 -500 watts each
   (k) flow rate range, 2-20 scfm
   (l) flow regulation, indexing orifice plate

4. Mass Sampling Turret
   (a) filter diameter, 142 mm - glass fiber
   (b) support screen (removable), 100 mesh stainless steel screen on perforated plate
   (c) number of active samples, 5 +1 stand by position
   (d) sealing method, neoprene O-rings
   (e) indexing motion, air cylinders and microswitches

5. Electron Microscope Sampling Turret
   (a) filter diameter, 47 mm - Nuclepore
   (b) support screen (removable), 100 mesh stainless steel screen on perforated plate
   (c) number of active samples, 5 +1 stand by position
   (d) sealing method, neoprene O-rings
   (e) indexing motion, air cylinders and microswitches

* See Phase I Report, Page 36.

Table 1 (continued)

6. Secondary Diluter
   (a) length, 18"
   (b) porous tube diameter (inside), 0.75"
   (c) outer tube (manifold) diameter, 3"
   (d) inlet diameter, 0.88"
   (e) outlet diameter, 0.88"
   (f) porous tube material, sintered stainless steel - 2 μm pore size
   (g) manifold tube material, aluminum - schedule 40
   (h) number clean-air inlets, 5 (solenoid-valve controlled)
   (i) clean-air regulation, line orifice
   (j) flow rate range, 0.2-1.0 scfm

7. Electrical Aerosol Analyzer
   (a) particle size range, (0.006 - 0.7 μm)
   (b) flow rate, 48 lpm
   (c) time interval for operation cycle, ∿3 min

8. Auxiliary Equipment
   (a) sample flow pipe fittings, Cherry-Burrell
   (b) sample flow prime mover, AF-33 Roots-Connersville Blower, 5-40 scfm (Primary Sampling Circuit)
   (c) vacuum pump, 26" Hg @ 4 scfm (Secondary Sampling Circuit)
   (d) flowmeter, 1000-2B Datametrics, 0-60 scfm (hot wire)
   (e) bleed valve, 2" motorized ball valve and 1" manual needle valve
   (f) clean-air supply, dryer and ultrafine filters
   (g) flow dampers, two in series - 8" diameter/33" long
   (h) sample flow control, two 3-way control valves (1"-main sample flow control, 3/4"-secondary sample flow control)

9. Sound Enclosure
   (a) outer box, 3/4" plywood
   (b) inside box, 3/4" plywood
   (c) outside dimensions, 82-3/4" x 39-1/4" x 36-3/4"
   (d) insulation, 4" foam with 1/16" lead sheet at foam center

Specification of the extracted sample flow rates depends on the engine power setting except for climb-out and take-off. This was true because the sonic condition was approached at the engine's exit plane and sampling at this rate would cause severe flow complications resulting in modification to the extracted exhaust particles. The flow through the nozzle was therefore limited to a local Mach number of 0.8. Since isokinetic sample flow was maintained otherwise and that the cross-sectional area of the extraction nozzles was fixed, the sample flows were specified. The range was 0.5 to 2.8 scfm for engine power settings of idle to take-off for the present sampling system.

During the acquisition of a sample set - mass and microscopic samples at a given engine power level - each sample was obtained in turn because of operational restraints. The operational procedure is described in a later section. The restraints resulted from the fact that the control valves were located downstream from the sample collection sites and that the total flow must be continuously monitored to maintain the desired flow conditions for particle collection. This was especially important for the mass sample because the sample flow enters directly in the determination of mass emission rate for the engine. In order to measure the total flow, the secondary sample line was closed. The control valves were located downstream from the particle collection sites to eliminate particle deposition within the valve assembly. Otherwise, particulate material would eventually build-up on the internal mechanism and subsequently be dislodged at some later time when a sample was being collected.

The following flow data gives the calculated Reynold's number (N_R) range at three locations within the sampling system. (See Table 2).

Location	Internal Diameter	Flow Range (scfm)	N_R
sample lines on probe assembly	1/4"	0.13 to 0.70	1.50×10^3 to 8.39×10^3
flexible coupling	3/4"	0.5 to 2.8	9.99×10^3 to 5.60×10^3
tubing upstream from mass sampling turret	2"	7.2 to 11.2	5.40×10^3 to 8.39×10^3

The Reynold's numbers suggest that the flow (if fully developed) would be intermittent between the laminar and turbulent flow regimes. These flow conditions were selected to provide conditions as near to laminar flow as possible to reduce the deposition of particles (bulk motion of the core flow "sweeping" the wall is enhanced during turbulent conditions and therefore increases deposition rates for submicron particles). Practical constraints also existed in regard to tube diameters on both the probe assembly and intermediate tubing. The diameters selected comprise the two requirements. All bends were gradual, eliminating preferential deposition at these points.

The measurement of the extracted sample flow from the engine was not directly obtained. Instead, the total flow after dilution on the main sample flow was measured. At this point, the flow has been cooled. Also, the total flow meter (hot wire anemometer) measured the total sample both in the sample position and the by-pass position. Through regulating the dilution air flow to the diluter, subtraction of this flow from the total flow as measured by the flow meter yielded the net sample flow. Consideration of errors is important as two large values are utilized to obtain a relatively small value. To minimize the uncertainty in the sample flow measurement, the flow meter as selected gave the best accuracy available -- about 2% or $\sim\pm$ 0.05 scfm while the dilution flow was repeatable

to within 0.1 scfm. The maximum error that could result occurs at idle and was on the order of 10%. This was considered reasonable when realizing the alternatives of measuring the sample flow directly and the associated problems of particulate deposition and sample modification.

Regulation of the sample flow was achieved through preselecting the dilution flow rate and providing the necessary pressure drop across the sampling system. A rotary vacuum pump served as the prime-mover for the bulk of the flow through the system. Two bleed valves located immediately up-stream from the rotary pump regulated the pressure recovery across the pump and thus the flow rate through the pump. The 2" bleed was electrically operated while the 1" bleed was manually operated. Both bleeds were adjusted remotely (within the control room): the 2" bleed was motorized with a 10 sec delay and the 1" bleed valve was physically located at the control center and connected by a sufficiently long hose. In practice, the 1" bleed was unnecessary as adequate flow control could be maintained with the 2" bleed alone. The flow dampers were installed to remove flow oscillations which propagated upstream from the rotary pump and induced a false flow indication into the hot-wire anemometer.

An oil-less vacuum pump was used to maintain flow through the secondary loop of the sampling system. For the particle analysis sampling turret, the flow was approximately 0.2 scfm. A rotameter and regulating needle valve was installed to visually check and adjust the flow. Flow through the EAA was 1.7 scfm and near the capacity of the vacuum pump. Simultaneous operation of the sampling turret and EAA was prohibited because of the control valve and was undesirable because of the flow complications that would occur at the tee above the sampling turret.

Air to the primary and secondary diluters was supplied as conventional compressed shop air, dried and filtered to

eliminate the addition of foreign particulate material. A pressure regulator and orifice-plate indexer (varying orifice diameter) was used to provide dilution air. Electrical heaters were also installed to exercise control over the final sample flow temperature and therefore provide flexibility in approaching the dew point of the diluted sample.

The substrates on which the particulate samples were deposited are given in Table 2. The glass fiber filters were used for the collection of a bulk sample suitable for gravimetric weighing. Both the Nuclepore filters and electron microscope grids were used to collect the samples for microscopic analysis. The grids were cemented directly onto the Nuclepore filter slightly off-center to prevent particle bias. Several grids were cemented to each Nuclepore. Brownian diffusion served as the deposition mechanism onto the grids by virtue of the low filter face velocity.

2.2 Mechanical Design of Sampling System

Design of the sampler's individual components was directed to meet the system flow specifications. This included the hardware development of the sampling turrets, the flow control for the diluter, the sampling probe, diluter, and the air-processing unit. In addition, the selection of commercially available components was regulated by the overall flow requirements.

Therefore, this section is devoted toward the discussion of the hardware comprising the sampling system. The system consists of the following sub-assemblies:

- sampling probe and manifold
- flexible coupling
- diluter

Table 2

LIST OF PARTICLE COLLECTION SUBSTRATES
USED IN SAMPLING SYSTEM

1. Glass Fiber Filters: Gelman Type AE, 142 mm dia.

   Purpose: collection of particulate bulk sample for gravimetric analysis

2. Membrane Filter: Nuclepore filter - 0.03 micron pore size, 47 mm dia.

   Purpose: collection of exhaust particles for microscopic analysis and support of electron microscope grid

3. Electron Microscope Grid: carbon coating on 200 mesh copper grid, 3.05 mm dia.

   Purpose: collection of exhaust particles for direct analysis with electron microscope

4. Electron Microscope Finder Grid: Formvar coated grids on H2 London finder grid

   Purpose: permits repeated analysis of same exhaust particles through identifying rotation on grid surface

- sound enclosure containing:
  - mass sampling turret
  - particle analysis sampling turret
  - electrical aerosol analyzer
- air processing unit containing:
  - rotary & GAST vacuum purps
  - total flow meter
  - flow control valves
  - modulating bleed valves
  - flow controller for diluter
- remote control panel

In the design of the sub-assemblies either transporting or collecting the exhaust particles, three guidelines were maintained:

1. The length of transport tubing between the engine and sample collection points would be minimized.
2. The interior surface of the tubing and sub-assemblies handling the particles would be smooth and uninterrupted wherever possible.
3. Abrupt changes in flow direction, velocity, and area would be avoided.

The application of the first guideline led to immediate complications. In order to minimize the length of transport tubing, complete particle collection must occur within the engine test cell. With acoustic sound levels in excess of 160 dB, "hands on" operation of the equipment was impossible. Manual operation of the sampling system was unacceptable from the standpoint that engine shut-down was required between each sample set or engine power setting. Therefore, the sampling system was designed to operate by remote control. Also, the test cell environment appeared too harsh for the electrical aerosol analyzer resulting in the design of a special sound enclosure.

In maintaining smooth internal surfaces for the transport tubing, smooth Cherry-Burrel fittings and seals were selected for all junction points upstream from the sample collection points. Use of these fittings proved very useful in that

they made the assembly and disassembly for cleaning and shipment of the sampling system easier to handle.

Further promoting an uninterrupted interior surface for the tubing, the flow control valves were located downstream from the sampling turrets. The reasoning here was that there is no way in which to control the internal geometry of commercially available valves and the design and fabrication of custom valves would be prohibitively expensive. Locating the control valves downstream, therefore, eliminated this problem, but introduced restrictions on the operating procedure of the sampling system as described later.

The following discussion involves the major system components and is taken in the same sequence as the sample passes through the system. Table 3 is a comprehensive list of the important components or special materials required for fabrication.

2.2.1 Sampling Probe Assembly

The sampling probe assembly mounts directly behind the engine's exit plane. Figure 2 shows the assembly drawing for the sampling probe. The basic design features corresponded to the sampling probes obtained from United Airlines. The support structure for the extraction nozzles and sample lines exhibited a "diamond" shape. The extraction nozzles were located at the midpoint of each leg of the diamond. The use of this sampling probe at NAFEC evaluated the performance and durability of the probe.

The design of the extraction nozzle is shown in Figure 3. The leading edge of the nozzle extended about three diameters upstream from the support structure based on the outside diameter of the sample line. However, the support structure was beveled to form the shape of a wedge and therefore reduce local flow perturbations in the vicinity of the leading edge of the extraction nozzle. Silver solder was used to secure

Table 3

LIST OF MAJOR COMPONENTS COMPRISING SAMPLING SYSTEM

1. Absolute filter: 2C1600 "Camgridge Absolute Filter", flow rate = 50 scfm, ΔP = 0.82" H_2O, D.O.P. penetration = 0.001%.

   Kewaunee Sci. Equip., Adrian, Mich. 49221

2. Insulation: 6' long, 3/4" thick, max. temp. = 220°F.

3. Electrical heater: AH-3 cartridge heater, 10-1/2" long, 1/2" NPT both ends, 120 V and 500 watt capacity.

   IIT Vulcan Electric, Northfield, Ill.

4. Flow damper: UR2 Silencen, 8" O.D. x 33" long.

   Universal Silencer, Stoughton, Wisc. 53589

5. Ball valve - 2": 10 second delay between full-open and full-close, 110 V-60 cycle actuator.

6. Flexible coupling: 3/4" I.D. flexible metal hose, 1" Male Cherry-Burrell each end.

   Inside liner: 0.004" x 4" wide Type 304 S.S.

7. Pyrometer: Simpson No. 29, 0-500°F.

8. Sound insulation: 3' x 16', 2-1/2 lb sheet lead, 240 lbs and untrimmed, 50" x 75" foam sheets, 2" thick, plain surface Soundcoat Branch Sound Foam without adhesive.

9. Pressure regulator: Parker Hannifin Model 06E15B18A.

10. Dilution air supply filter: Parker Hannifin Coalescing Filter, 1/2" port, Model 12F35F.

11. Secondary diluter valves: solenoid operated, 1/4" gas, 100 psi.

12. Dilution air dryer: Serfilco Model SF-A38-1/2"-MD4, Filter/Dryer.

    Service Filtration Corp., Northbrook, Ill. 60062

13. Flow meter: hot-wire anemometer, Model 800LM flowmeter with transducer and readout, Model 1000-2B, 0.2-60 scfm.

    Datametrics, Wilmington, Mass. 01887

Table 3 (continued)

14. Rotary vacuum pump (Roots Blower): Roots-Connersville AF blower frame size no. 33, 3 HP motor (1750 rpm), 3-Phase, 230V, 0 scfm at 10" Hg vacuum.

    Dresser Industries, Inc., Connersville, Ind. 47331

15. Vacuum pump: Gast No. 0740-V1054A-R180, oil-less, 110 V-60 cycle motor.

16. Control valves: 1" valve with QC25B actuator, 3/4" valve with AC25B actuator.

    Quality Control, Malden, Mass. 02148

17. Porous tubes:

    Diluter: 1/2 micron pore size, 2" I.D., 1/16" wall thickness, rolled and welded, 6' long.

    Secondary diluter: 1/2 micron pore size, 1" O.D., 1/4" I.D., 18" long.

    Mott Metallurgical Corp., Farmington Industrial Park, Farmington, Conn. 06032

18. Electrical Aerosol Analyzer, Model 3030, separate flow and control modules.

    Thermo-Systems, Inc., Minneapolis, Minn.

the nozzle to the sample line. The maximum engine exhaust temperature was approximately 1200°F while the silver solder melts at roughly 1300°F. Moreover, for the silver solder to flow, a special flux is required and consequently prevents the flow of solder into the sample stream. Loading on the nozzles was "into" the tube shoulder thus eliminating the possibility of actual loss.

The sample transport tubes on the probe's support structure remained separate until manifolded together outside the exhaust stream of the engine. The transport tubes as well as the support structure itself were secured without welds to permit expansion of the entire assembly. Figures 5 and 6 show the details comprising the manifold.

Figure 6 is a photograph of the sampling probe assembly. The extension of the support structure at the "points" of the diamond conform to the mounting requirements at the NAFEC test facility.

2.2.2 Flexible Coupling

A flexible coupling was required between the sampling probe assembly and the remainder of the sampling system. Whereas the sampling system was rigidly fixed, the engine during operation elongates due to thermal expansion. Therefore a flexible coupling was necessary. Due to the proximity of the coupling to the high temperature exhaust flow, elastomeric tubing was not acceptable. In contrast, commercially available metal hoses were not of sufficient internal smoothness to permit their use. As a consequence, a special flexible coupling was designed.

The design consisted of a stainless steel foil liner (0.004" thickness) inside a bellows-type flexible metal hose. For fabrication, the foil was bent over a mandrel, spot welded to maintain shape, and silver soldered to seal the joint. Next, the foil tube was inserted into the flexible

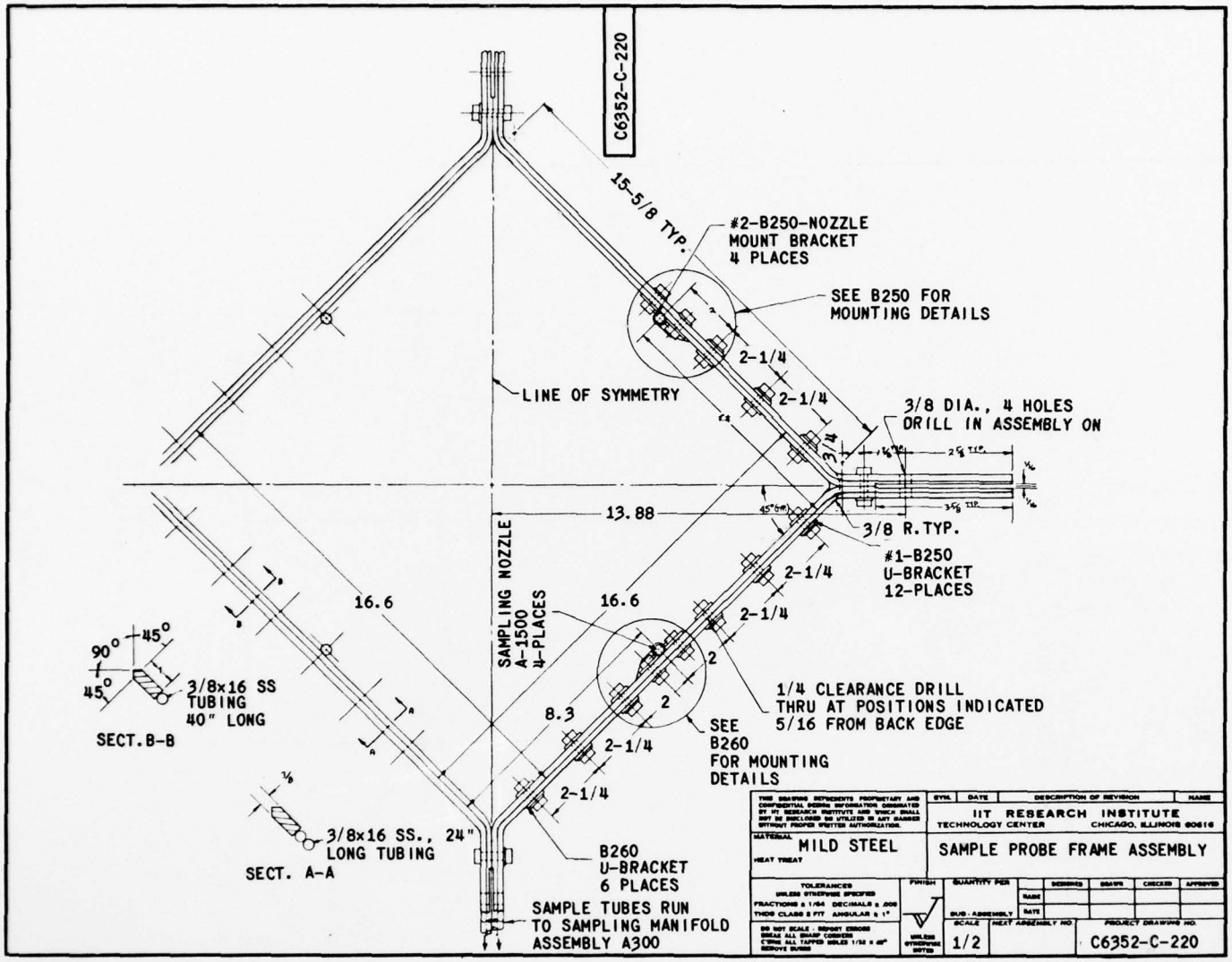


Figure 2

ASSEMBLY DRAWING FOR THE SAMPLING PROBE USED AT NAFEC

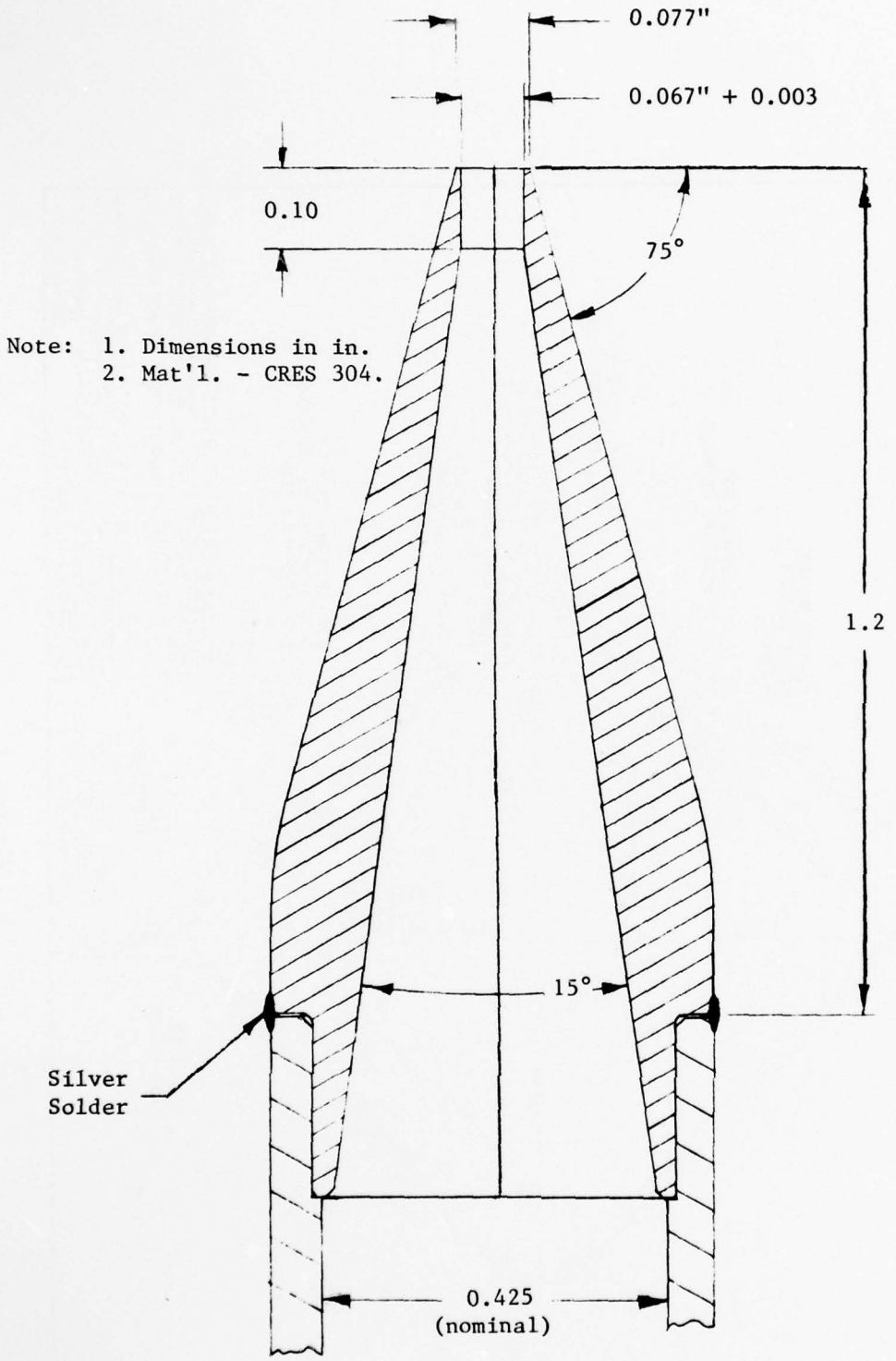


Figure 3

EXTRACTION NOZZLE DESIGN

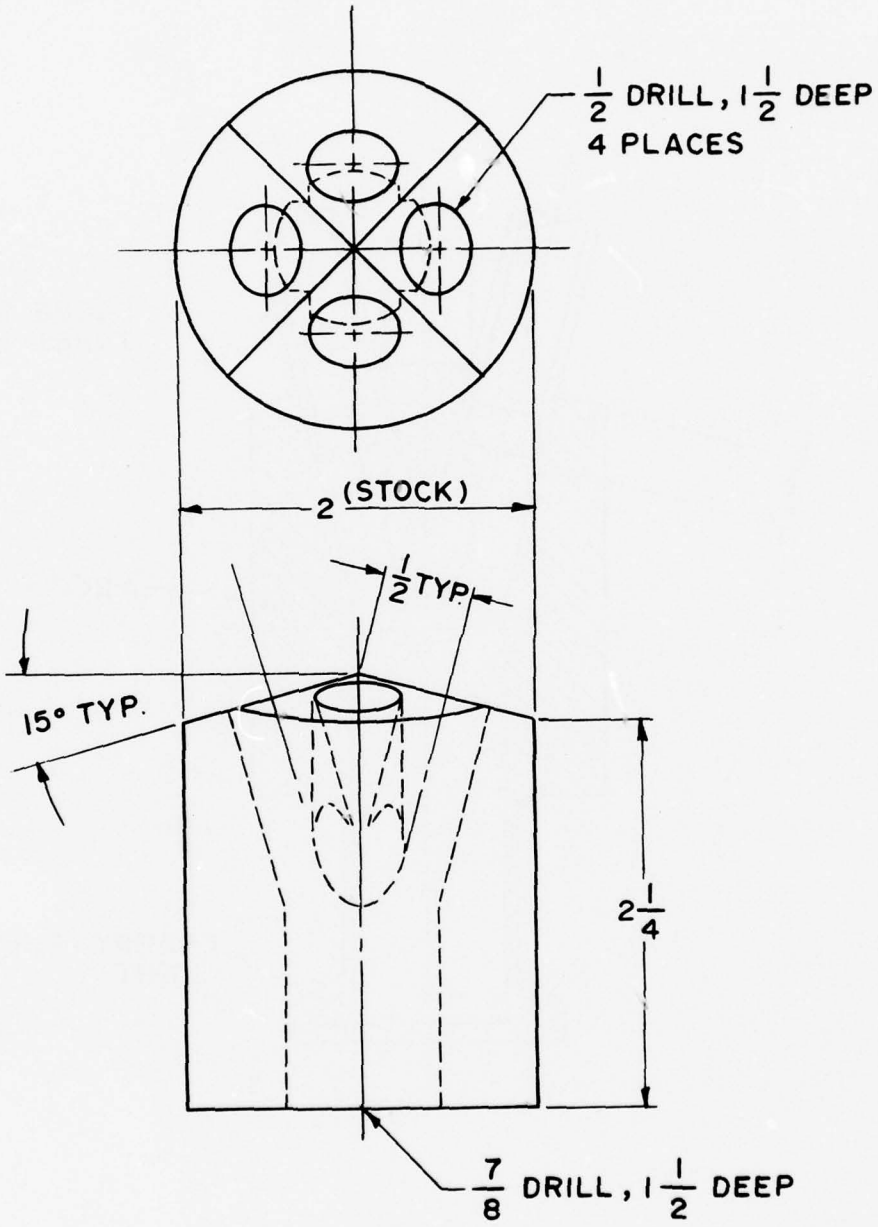


Figure 4

SKETCH OF THE SAMPLING PROBE MANIFOLD ASSEMBLY

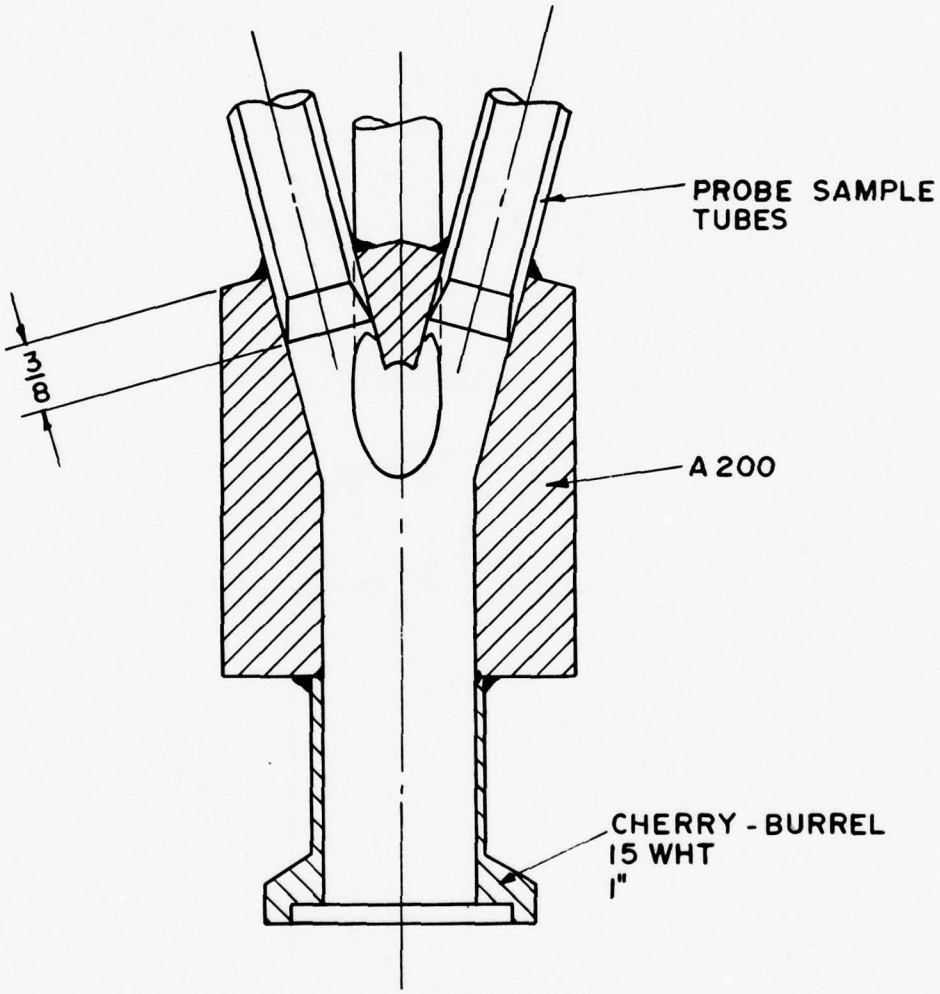


Figure 5

SECTION VIEW OF THE SAMPLING PROBE MANIFOLD ASSEMBLY

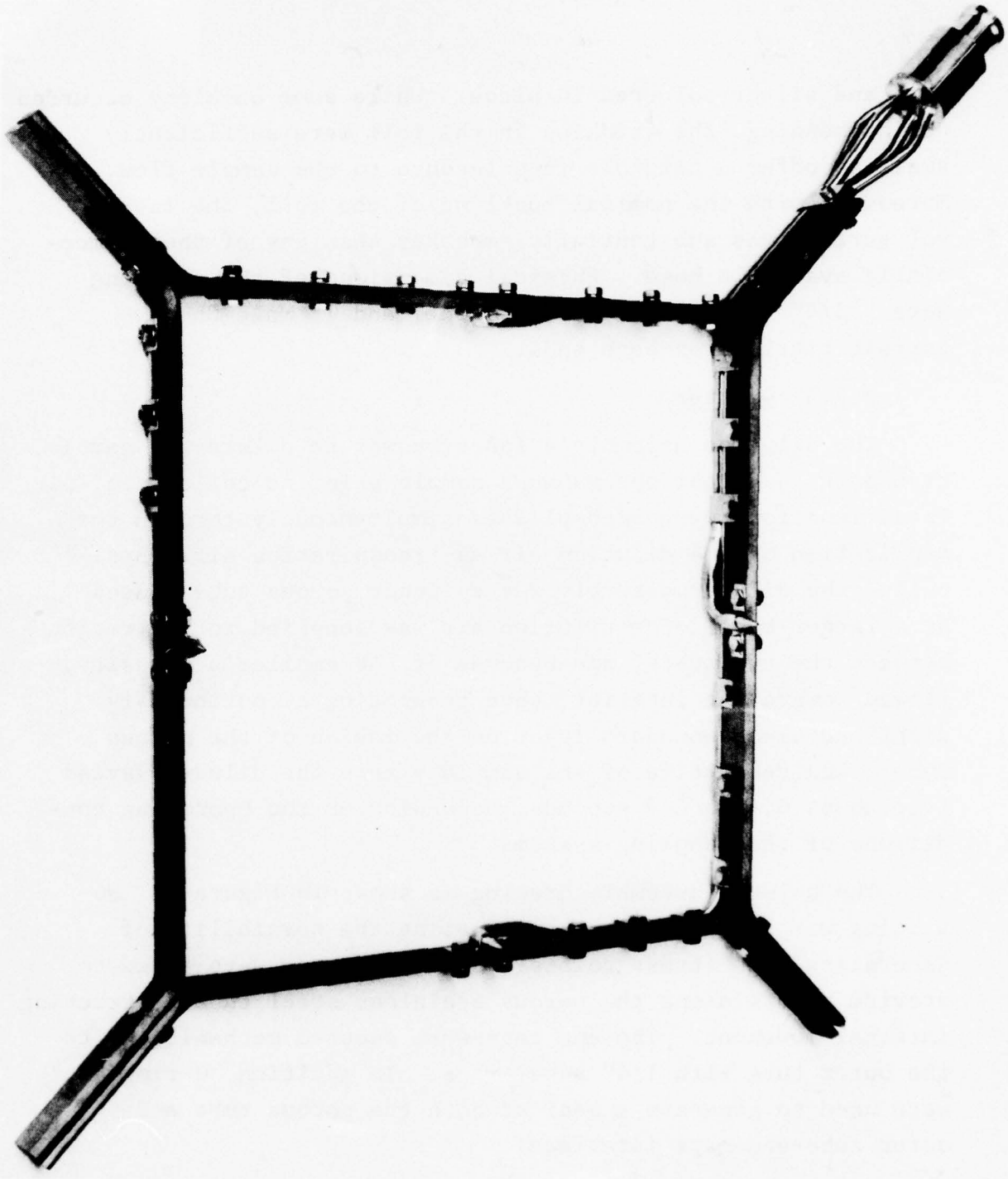


Figure 6

PHOTOGRAPH OF THE COMPLETED SAMPLING PROBE ASSEMBLY

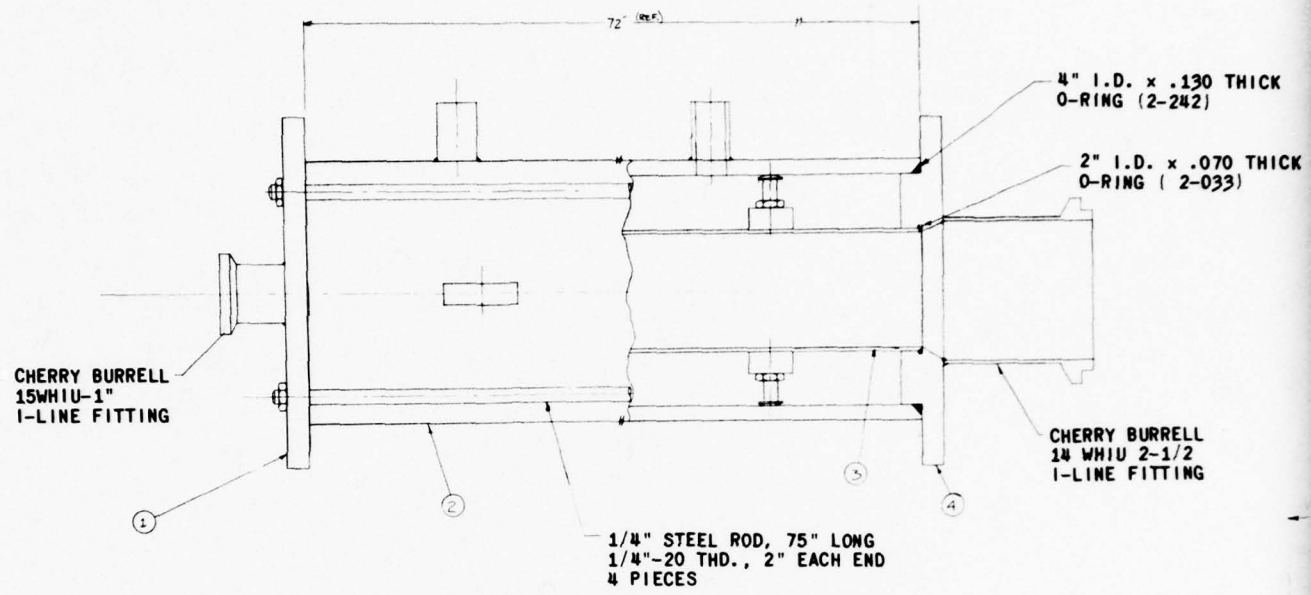
hose and silver soldered in place. While some buckling occurred during bending, the wrinkles in the foil were sufficiently small to offer negligible interference to the sample flow. Moreover, with the nominal buckling of the foil, the interval surface was substantially smoother than any of the commercially available hose. Physical dimensions of the coupling were: 3/4" inside diameter, 3' long, and 1" Male Cherry-Burrell fittings on both ends.

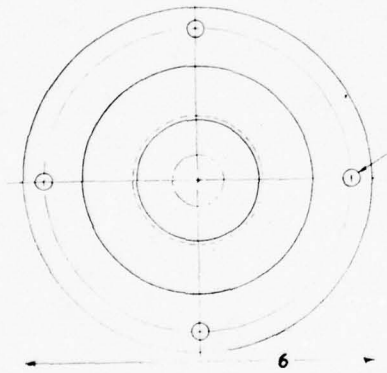
2.2.3 Diluter

The dilution assembly's function was to dilute the sample, transport, and cool the exhaust sample prior to collection. These functions were accomplished simultaneously through the application of the dilution air as transpiration air. Basically, the diluter assembly was an inner porous tube housed by a larger tube. The dilution air was supplied to the region between the two tubes, and because of the smaller's porosity, flowed toward the interior, thus generating a continuously displaced clean boundary layer on the inside of the porous tube. Residence time of the sample within the diluter varied from about 0.4 to 0.9 seconds, depending on the operating conditions of the sampling system.

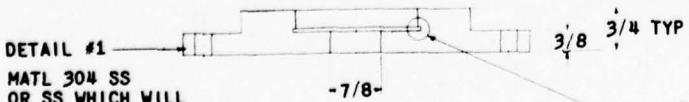
The diluter assembly drawing is shown in Figure 7. No welding was required, thus eliminating the possibility of generating high stress points. Support clamps were added to provide points along the porous stainless steel tube restricting internal movement. The end caps were secured mechanically to the outer tube with 1/4" steel rods. In addition, O-rings were used to generate a seal at both the porous tube and outer tube-end caps interface.

The outer tube of the diluter was fabricated from aluminum to reduce overall weight. The upstream end of the diluter was not in the exhaust stream and was also cooled by the supplied dilution air. Six lugs were provided on the tube surface to





SLIP FIT INTO
I.D. OF PART #2
TYP



DETAIL #1

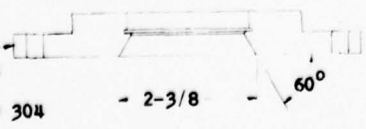
MATL 304 SS
OR SS WHICH WILL
WELD TO 304

MAKE .010..020 LARGER
THAN I.D. OF PART #3

TYPICAL

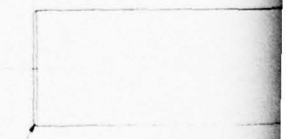
- 2 (REF) -

NOTE-UNDERCUT MAY BE
ALTERED PROVIDED THAT
THE INCLUDED AREA
REMAIN UNCHANGED



DETAIL #4
MATL: 304 SS
OR SS WHICH
WILL WELD TO 304

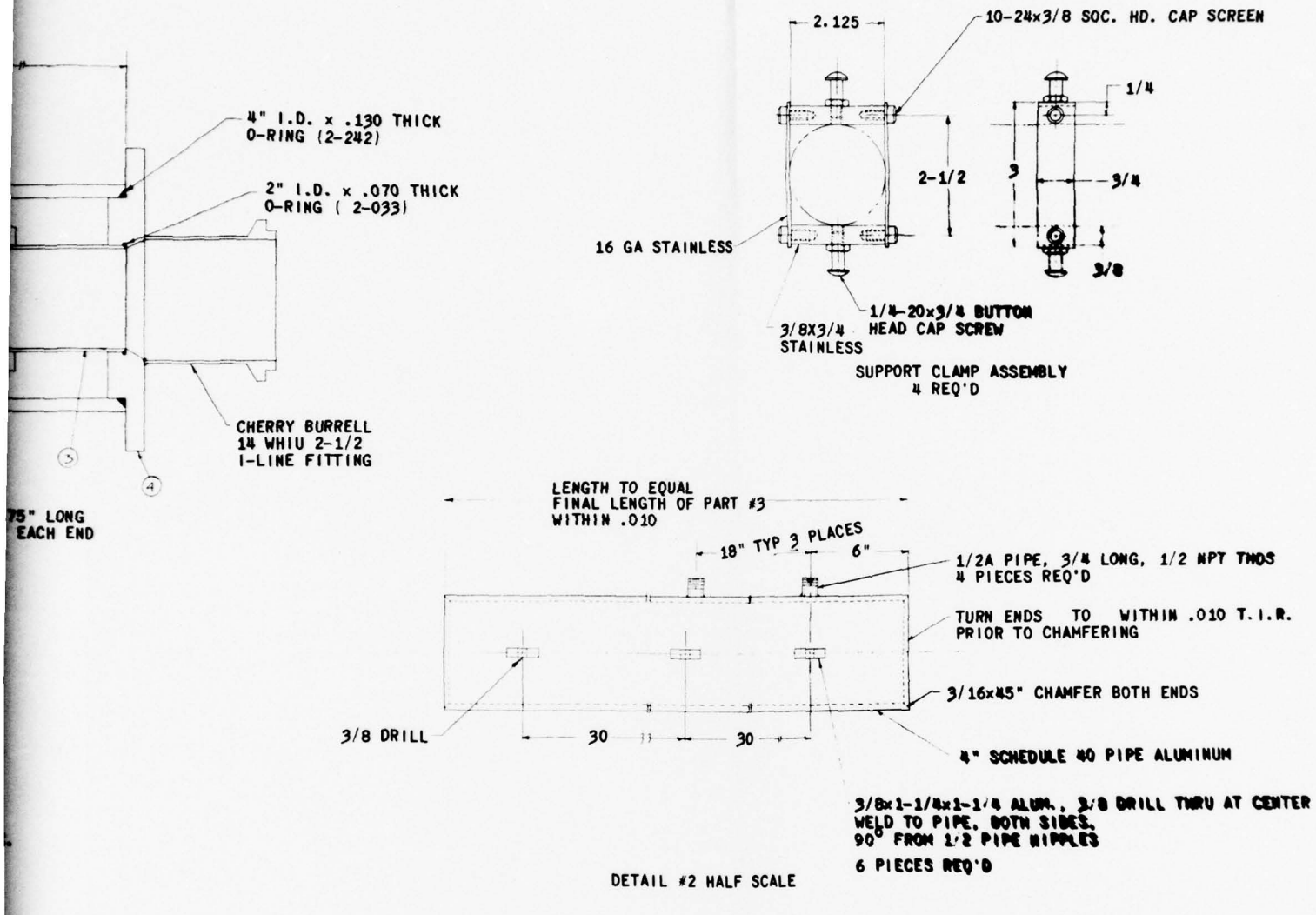
3/8 DRILL



DETAIL
MATL: P
2-1/8 O
SUPPLIE

Figur

ASSEMBLY DRAWING



THAT

Figure 7

ASSEMBLY DRAWING FOR THE DILUTER

facilitate installation within the test cell. Figure 8 is a photograph of the inlet side of the diluter showing the female 1" Cherry-Burrell fitting.

Later, the diluter was insulated with foam and secured with duct tape. A stand was made for the diluter supporting the assembly at the proper angle to match the flexible coupling and fitting leading to the sampling turrets where particle collection occurred.

2.2.4 Sampling Turret Assemblies

A substantial effort was spent on designing the two turret assemblies. The larger turret assembly was used to hold the glass fiber filters used in the collection of a bulk particulate sample. The smaller turret assembly held the Nuclepore filters and electron microscope grids for determination of particulate characteristics.

The turret or rotating wheel was selected as the most reliable mechanism to hold and manipulate the filter substrates. Since the introduction of the substrates to the sample flow had to be performed sequentially, two potential problems arose: the first was making and breaking the seal without the loss or contamination of the sample air, and second, adequately protecting the sample from the time of collection to the time of analysis or permanent storage. The turret mechanism was construed in such a way to meet these requirements and consisted of a two part assembly. The first part -- a turret plate and two cover plates -- was removable from the complete assembly. The turret plate itself was a circular disc with six filter seats machined into the top face, equally spaced about the center. Five of these seats were used to contain the filter substrates during a test, and were sandwiched between the two cover plates, top and bottom, during storage and transport. These cover plates served to seal and protect the collected sample. The sixth seat in the

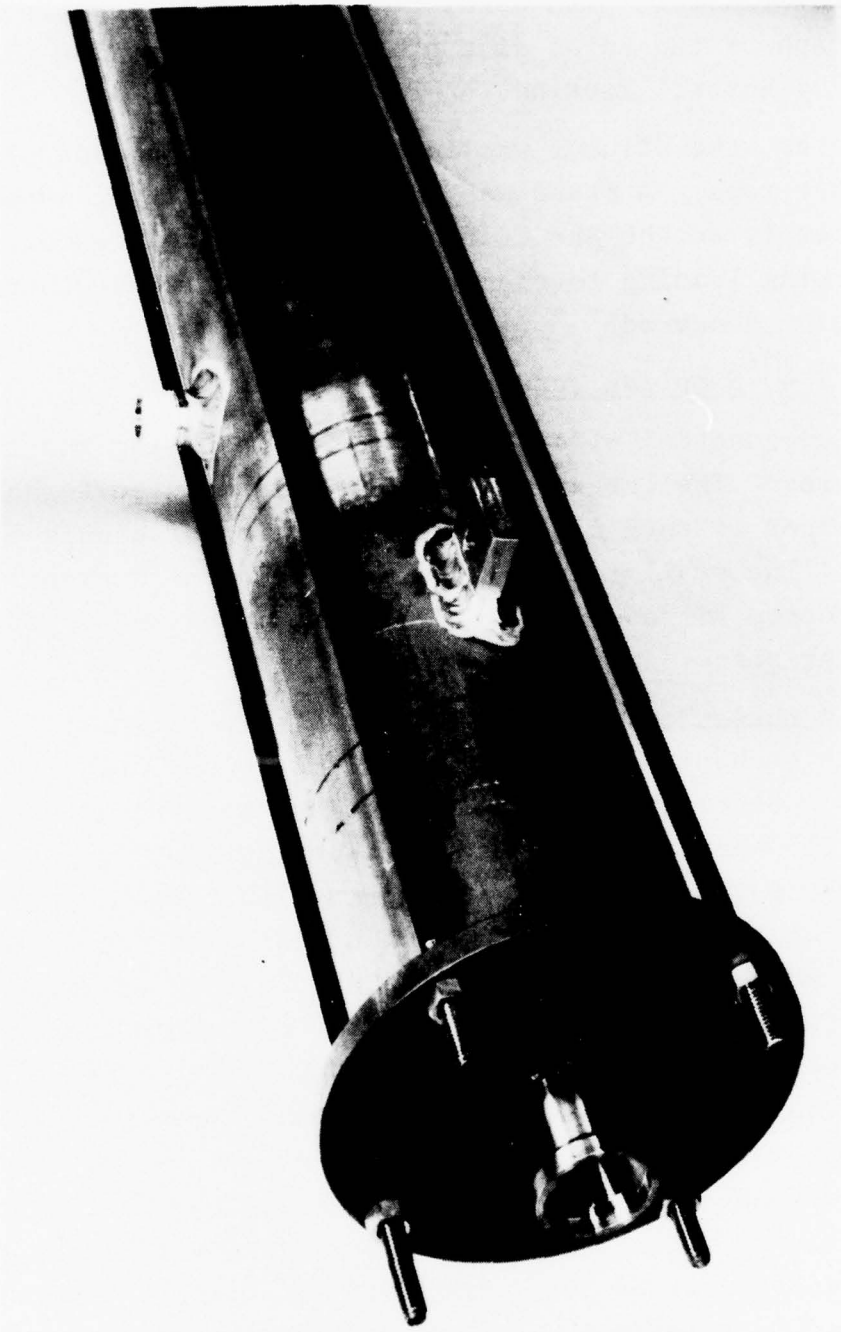


Figure 8

PHOTOGRAPH OF DILUTER ASSEMBLY FROM THE INLET SIDE

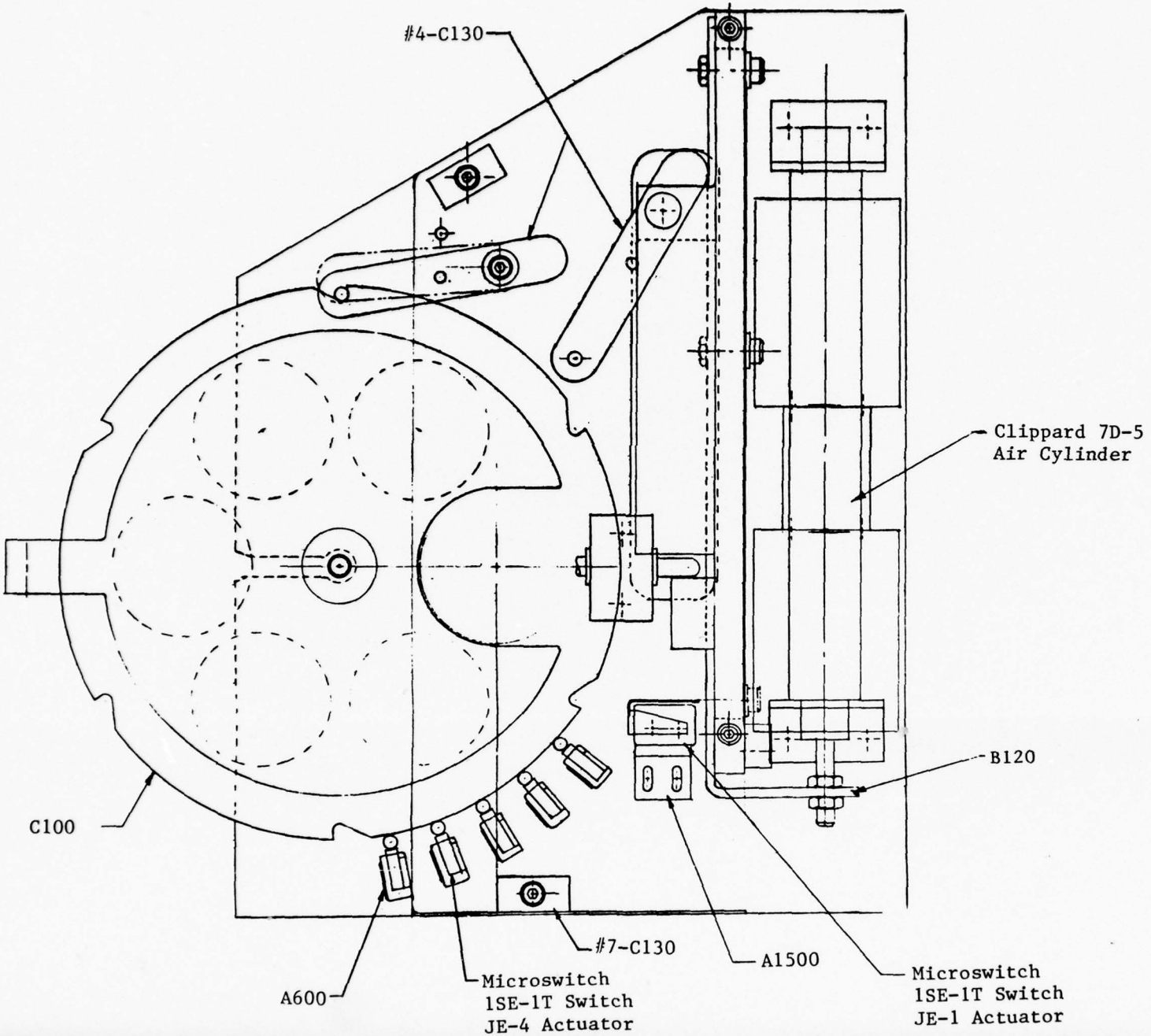
disc was a "dummy" which was exposed by a cut-out in the cover plates. The turret plate assembly was made removable in order to quickly exchange sample bearing substrates for clean substrates, in the event that more than one set of tests were desired from one engine under a given set of conditions.

The second part of the assembly was responsible for the indexing and sealing action of the sample substrates. This sub-assembly primarily consisted of an air-cylinder driven ratchet arm which indexed the turret plate one-sixth revolution per stroke. The motion of the ratchet arm activated a cam which raised a spring-loaded seal face from the sample substrate. This approach achieved an effective seal which did not inhibit the indexing motion of the sample turret. By setting a switch on the control panel, the seal could be maintained broken to allow the interchange of turret plates.

This basic design approach was used for both the mass sampling turret and the particle analysis sampling turret. The only fundamental difference between the two sampling turret assemblies was size; considerable design time was conserved through utilizing the same basic approach for both assemblies.

Pneumatic power was chosen as the principle source of motion in these assemblies for two reasons. First, air was being supplied to the system for dilution air, so no extra provisions were required for the pneumatics. Second, the motions used were well suited to the "all-or-nothing" nature of pneumatic systems. Where adjustments to the operating characteristics were necessary, the introduction of a pressure regulator or needle valve was sufficient, therefore minimizing the time and expense of system alterations.

Figure 9 is the assembly drawing of the particle analysis sampling turret. The direction of sample flow is from the top downward. Upstream from the substrate (above the thin backing



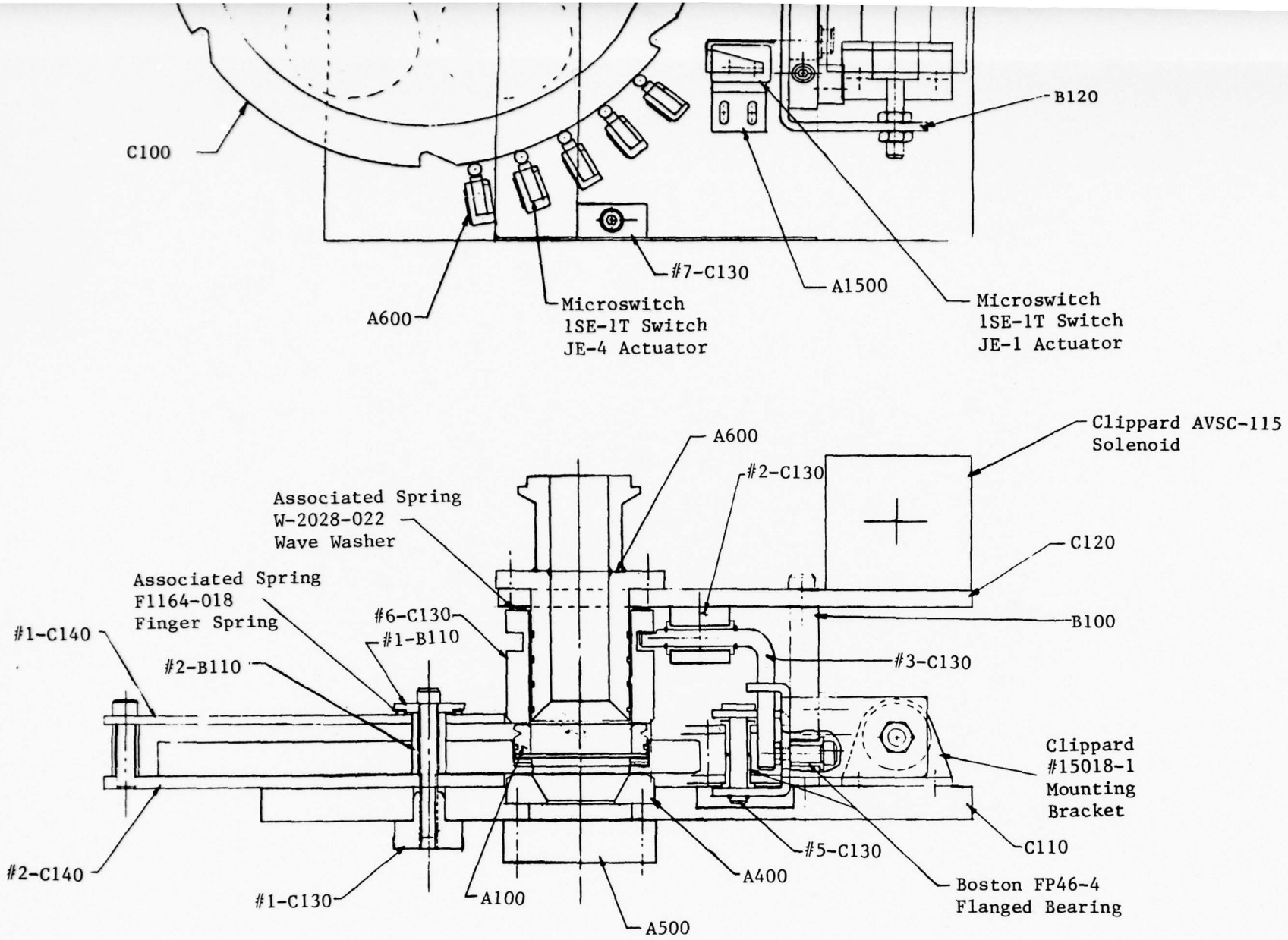


Figure 9

ASSEMBLY DRAWING OF THE PARTICLE ANALYSIS SAMPLING TURRET

Electron Microscope Target Turret Assembly

C6352-R-100

plate)* a translating collar compressed the O-ring seals to prevent leakage during sampling. During indexing, the collar raised to permit rotation of the turret plate. Figure 10 is a photograph of the smaller turret assembly showing the pneumatic actuating equipment, the microswitches, and the bounding plates. Figure 11 is a photograph of the turret plate assembly showing the location of the cover plates and the exposure of the "dummy" or stand-by substrate position.

Figure 12 is a sketch (not to scale) showing the location of all O-rings used to generate the required seal. All the O-ring grooves were cut deep and narrow relative to the "standard" groove in order to adequately secure the O-ring. Numerous indexing motions were applied to the turret assembly with no loss of O-rings. Leak tests were performed by inducing a vacuum to the system, closing, and observing the decay of vacuum with time. No detectable decay in vacuum was observed.

From Figure 12, note the lower O-ring at the bottom of the sealing ring. This O-ring in conjunction with a 47 mm diameter glass fiber filter generated a good seal around the very thin Nuclepore membrane filter. The O-ring and glass fiber filter in combination comply to the stainless steel backing screen. Cigarette smoke was used to check the deposit on the Nuclepore filter. Within one minute, the filter was choked and the pressure drop increased until the flow was virtually zero -- again an indication of no leaks. Examination of the Nuclepore filter indicated uniform deposition. Carbon black was then applied to a clean Nuclepore filter and choking did not occur, suggesting that jet exhaust should not plug the filter.

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* The backing plate for both substrates consisted of a porous plate -- 1/8" thick steel plate and 1/8" holes evenly distributed -- on top of which was spot welded 100 mesh stainless steel type 304 cloth.

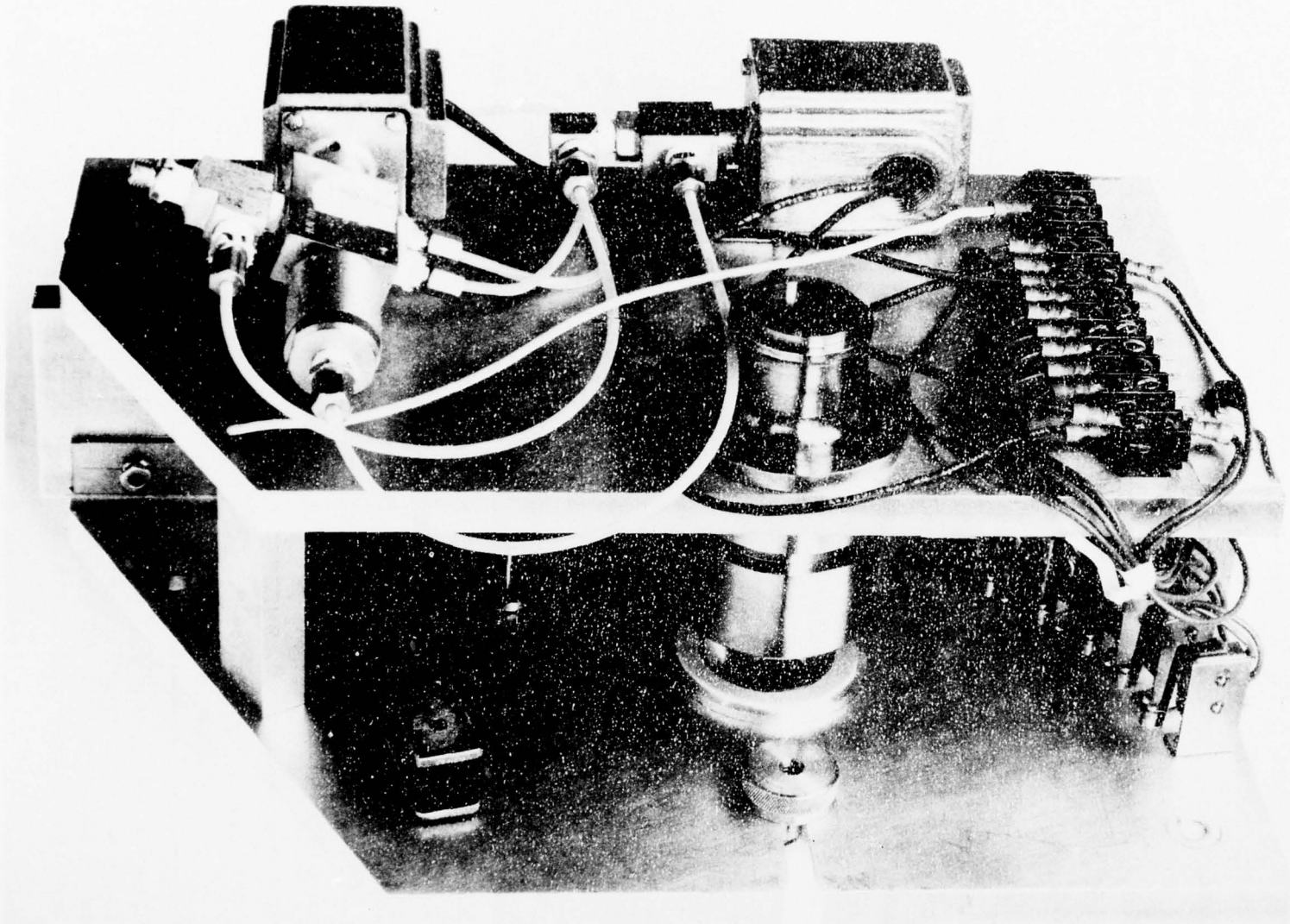


Figure 10

PHOTOGRAPH OF THE PARTICLE ANALYSIS SAMPLING TURRET ASSEMBLY
WITH THE TURRET PLATE REMOVED

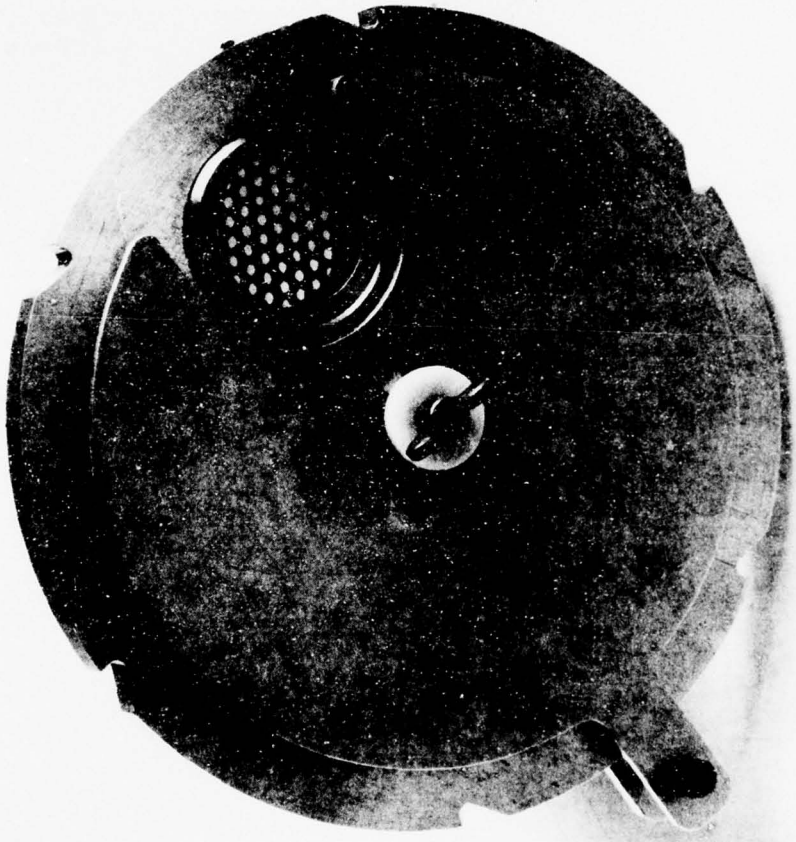


Figure 11

PHOTOGRAPH OF THE TURRET PLATE ASSEMBLY COMPRISING THE PARTICLE ANALYSIS SAMPLING TURRET

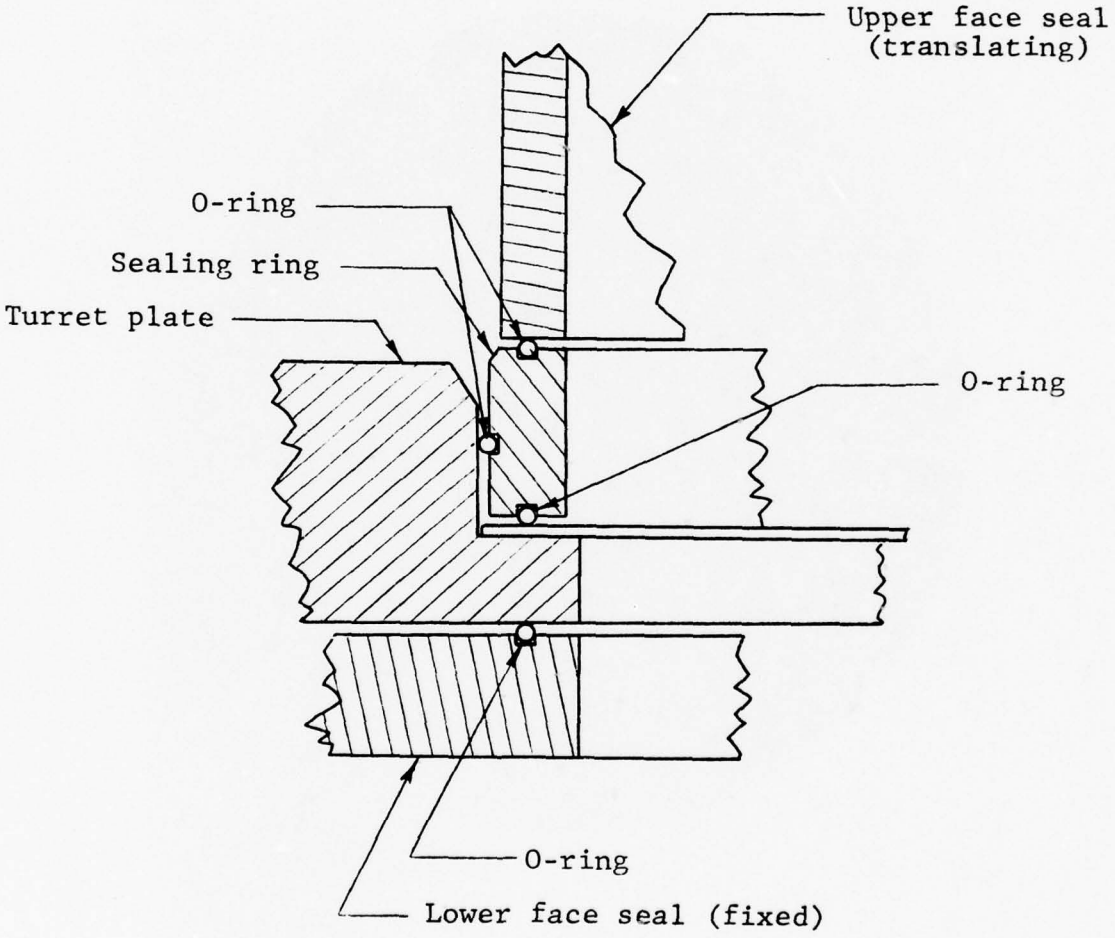


Figure 12

SKETCH SHOWING THE O-RINGS PROVIDING SEALS WITHIN THE PARTICLE ANALYSIS SAMPLING TURRET (NOT TO SCALE)

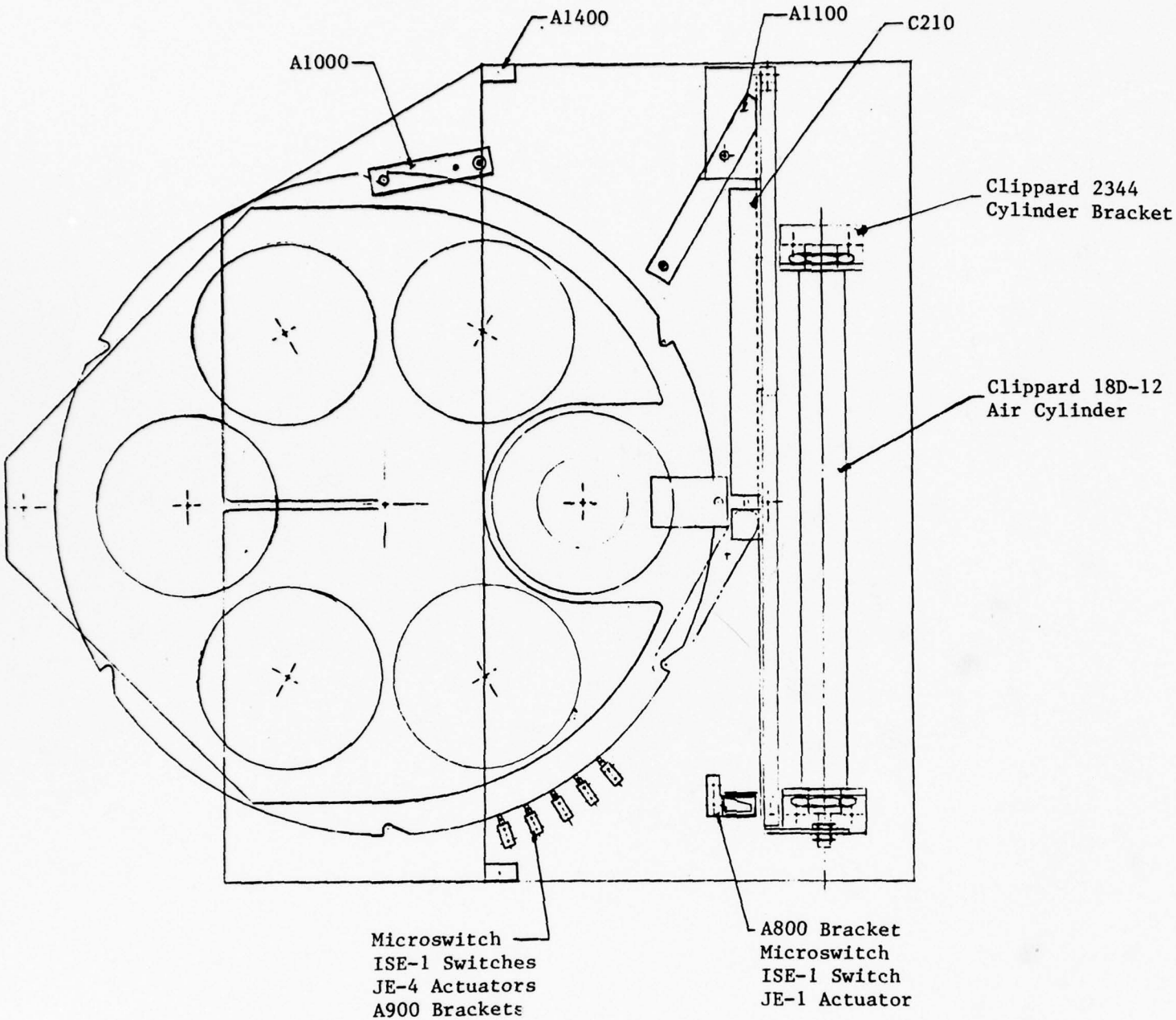
The mass sampling turret assembly drawing is given in Figure 13. The design features are seen to parallel those of the smaller turret assembly. In the side view of Figure 13, the flow is directed from the top downward where the flow expands to accomodate the diameter of the glass fiber filter.

A sketch (not to scale) of the O-ring location required for adequate sealing is shown in Figure 14. The lower sealing plate was stationary and therefore only one O-ring was required. A highly compliant O-ring was used here to maintain the necessary clearances for the indexing action. This lower O-ring was 1/4" in cross-sectional diameter and is identical to those used as rebounders in pin-ball machines. The O-ring grooves were also cut narrow and deep to prevent loss during the indexing action. The complete mass sampling turret exhibited a very slight leak detectable only by drift on the vacuum gage monitoring the internal pressure. This did not have any effect on the sampling measurements.

Figures 15 and 16 are photographs taken of the mass sampling turret assembly. Figure 15 shows the complete unit showing the relative location of the secondary diluter. Figure 16 is a close-up of the translating cone (makes the seal) and the tube extracting the sample for the secondary flow circuit. Figure 17 is a photograph of the turret plate assembly showing the location of the cover plates and the exposure of the stand-by substrate position.

2.2.5 Dilution Air Supply

Air flow to the primary diluter was regulated by precisely sized orifices. The air, prior to passing through the orifice, was both dried and filtered to avoid contamination of the sample. The location of the dilution air equipment was on the air-processing unit, but requires special consideration because



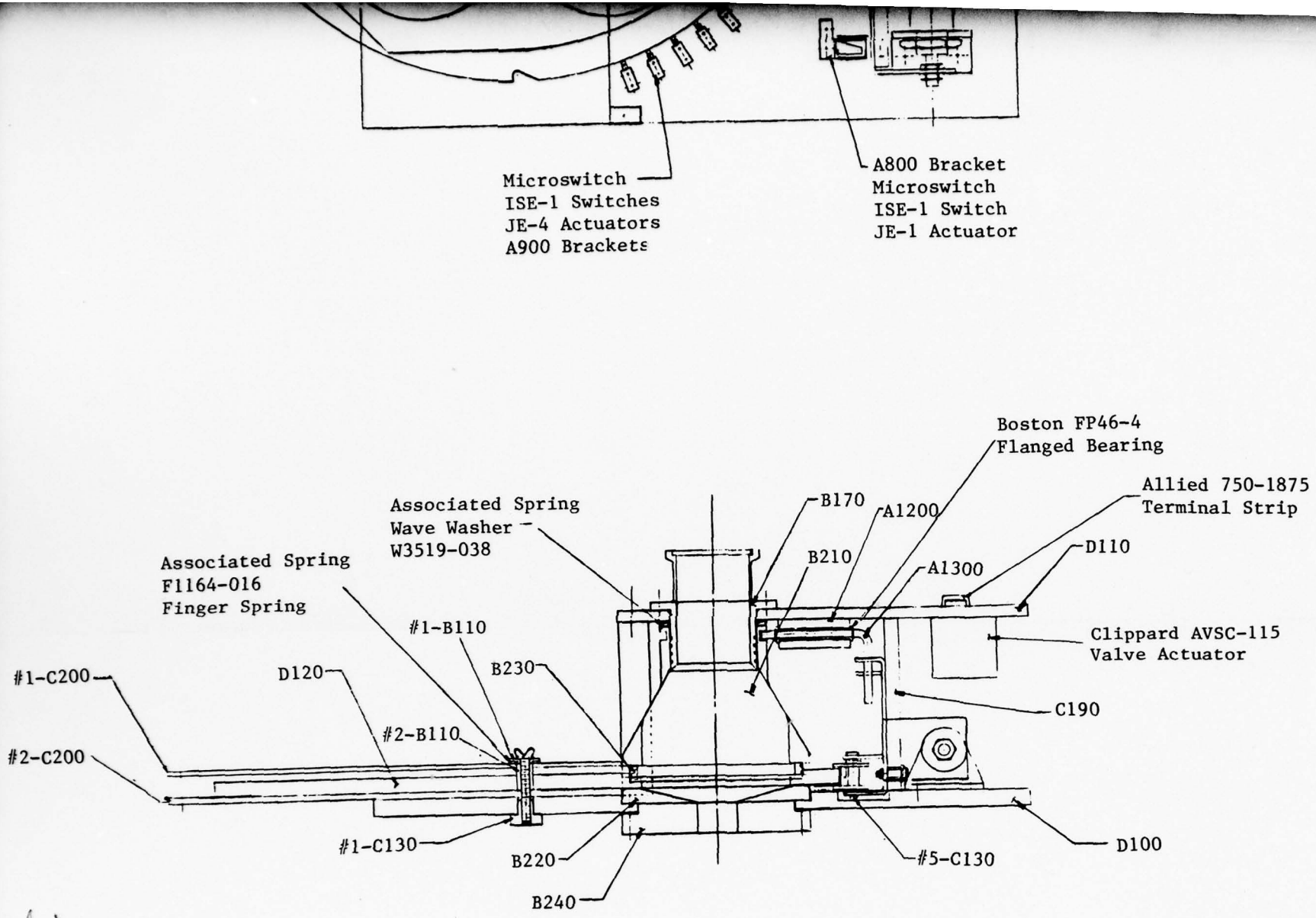


Figure 13

ASSEMBLY DRAWING FOR THE MASS SAMPLING TURRET

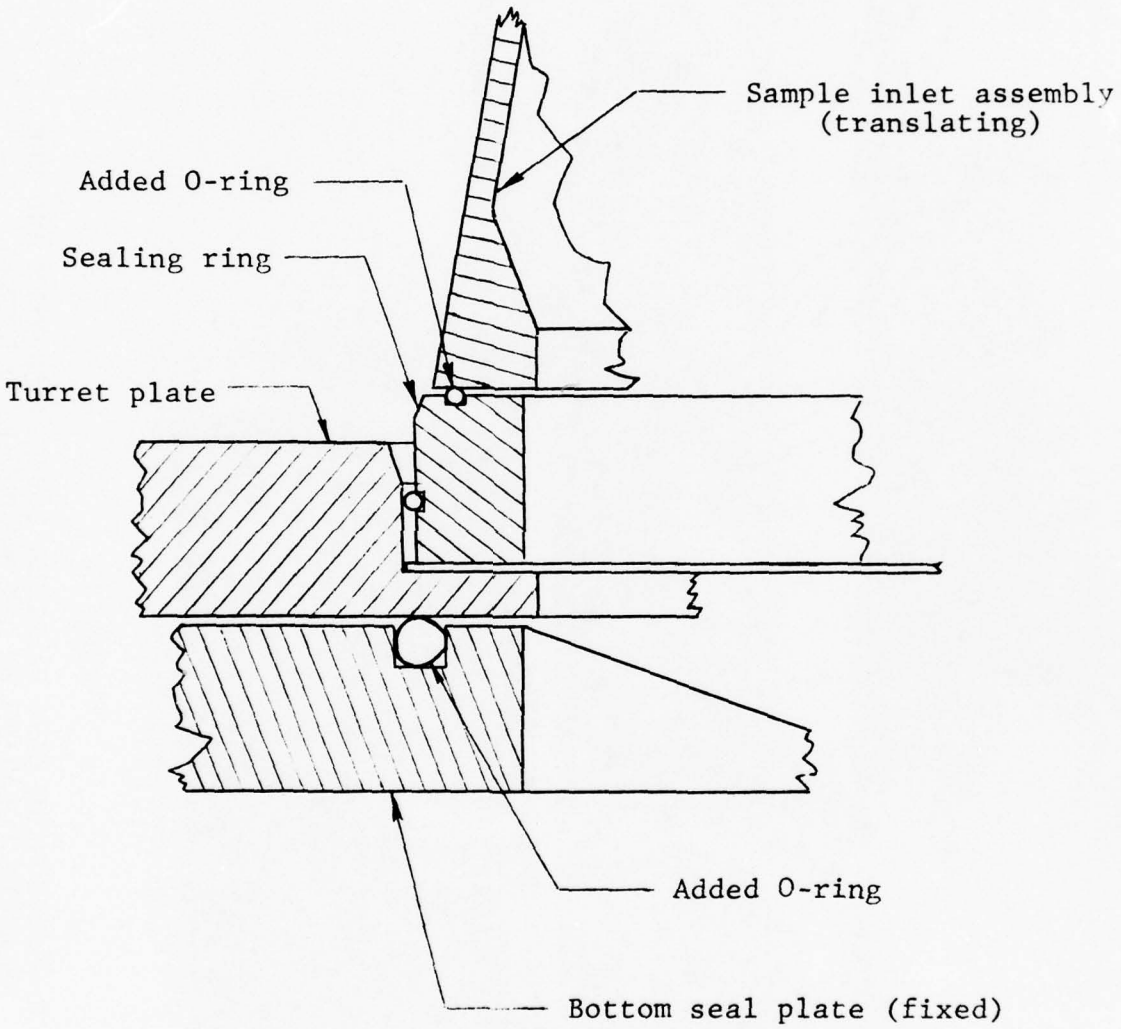


Figure 14

SKETCH SHOWING ADDED O-RINGS TO MASS SAMPLING TURRET
TO IMPROVE SEALING (NOT TO SCALE)

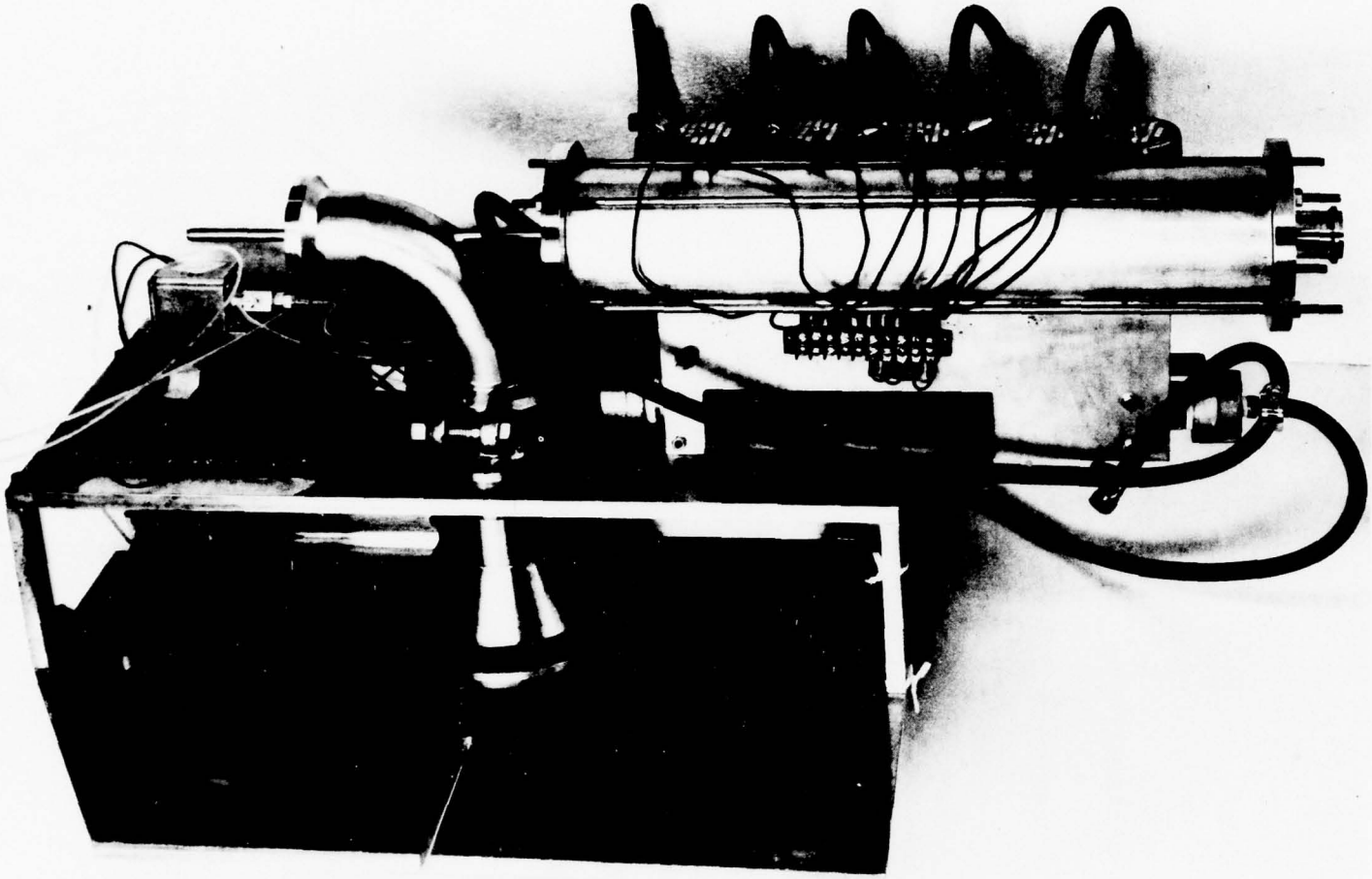


Figure 15

PHOTOGRAPH SHOWING THE MASS SAMPLING TURRET ASSEMBLY AND THE RELATIVE LOCATION OF THE SECONDARY DILUTER

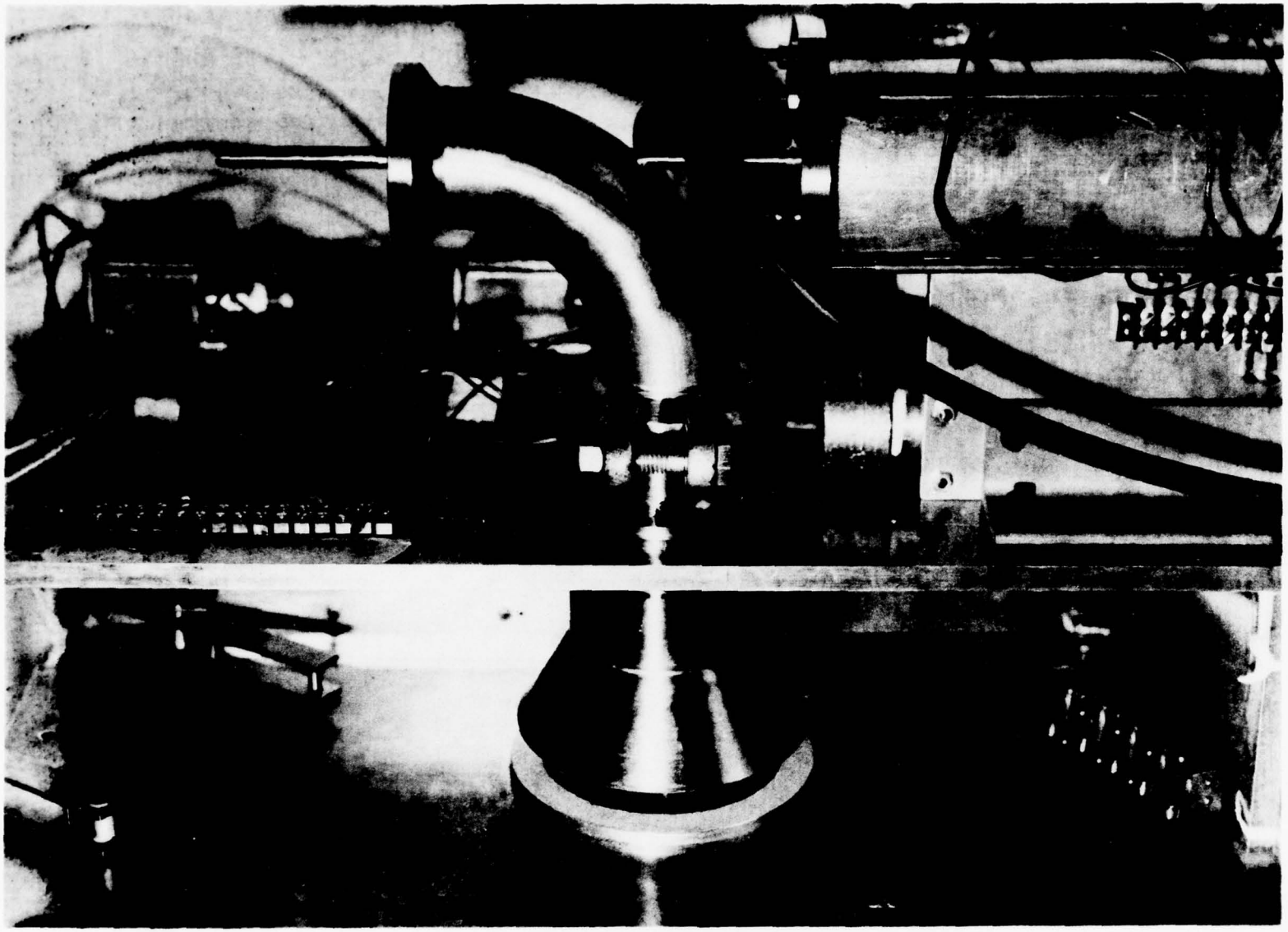


Figure 16

CLOSE-UP PHOTOGRAPH OF THE MASS SAMPLING TURRET ASSEMBLY SHOWING TUBE WHERE THE SECONDARY SAMPLE FLOW IS WITHDRAWN

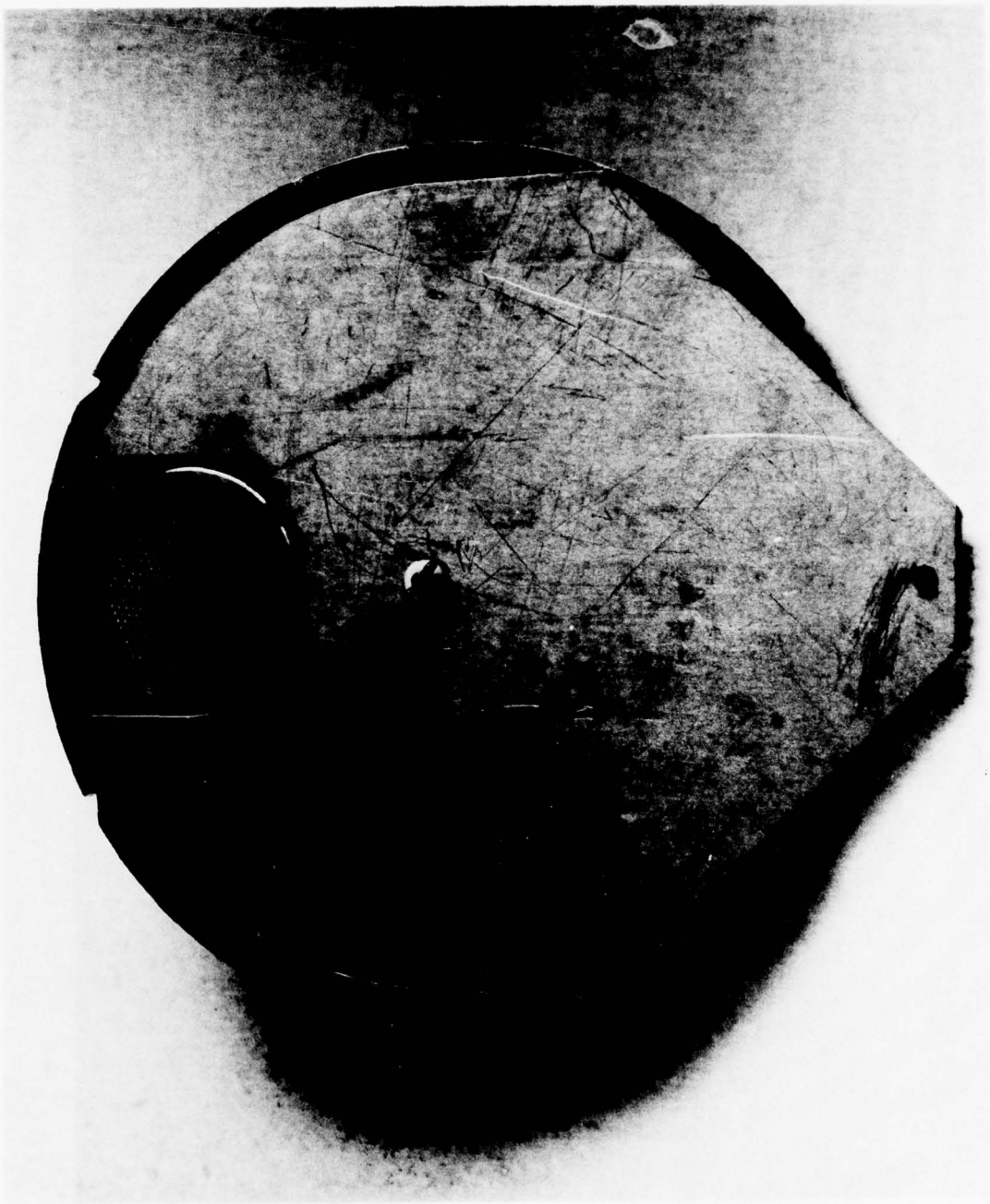


Figure 17

PHOTOGRAPH OF THE TURRET PLATE ASSEMBLY OF THE
MASS SAMPLING TURRET ASSEMBLY

of the mechanism constructed to perform the regulation of air flow rate.

The mechanism constructed to regulate the air flow to the diluter consisted of a series of orifices plated sequentially by diameter in an indexing slide. Translation of the slide introduced the orifices selectively into the air flow stream. A pneumatic cylinder activated by solenoid valves re-set the slide while a solenoid operated escapement assembly positioned the slide to the next orifice when activated. Figure 18 is the assembly drawing for the "orifice indexer". Teflon seals located in the indexing slide effectively sealed the orifice against leaks. By maintaining the upstream pressure at a pre-determined pressure (30 psig)*, the air flow was constant and reproducible. The individual orifices were designed in such a way that removal and replacement was a simple operation. The flow rates obtainable from the orifice indexer were as follows:

PRIMARY DILUTION FLOW RATES

Position No.	Flow Rate (scfm)
1	2.4
2	5.6
3	8.4
4	10.5
5	17.3

* The supply pressure to the orifice indexer was maintained at 30 psig to insure choked flow across the orifice at all times. A pressure regulator located upstream delivered this pressure for each of the orifice diameters without adjustment.

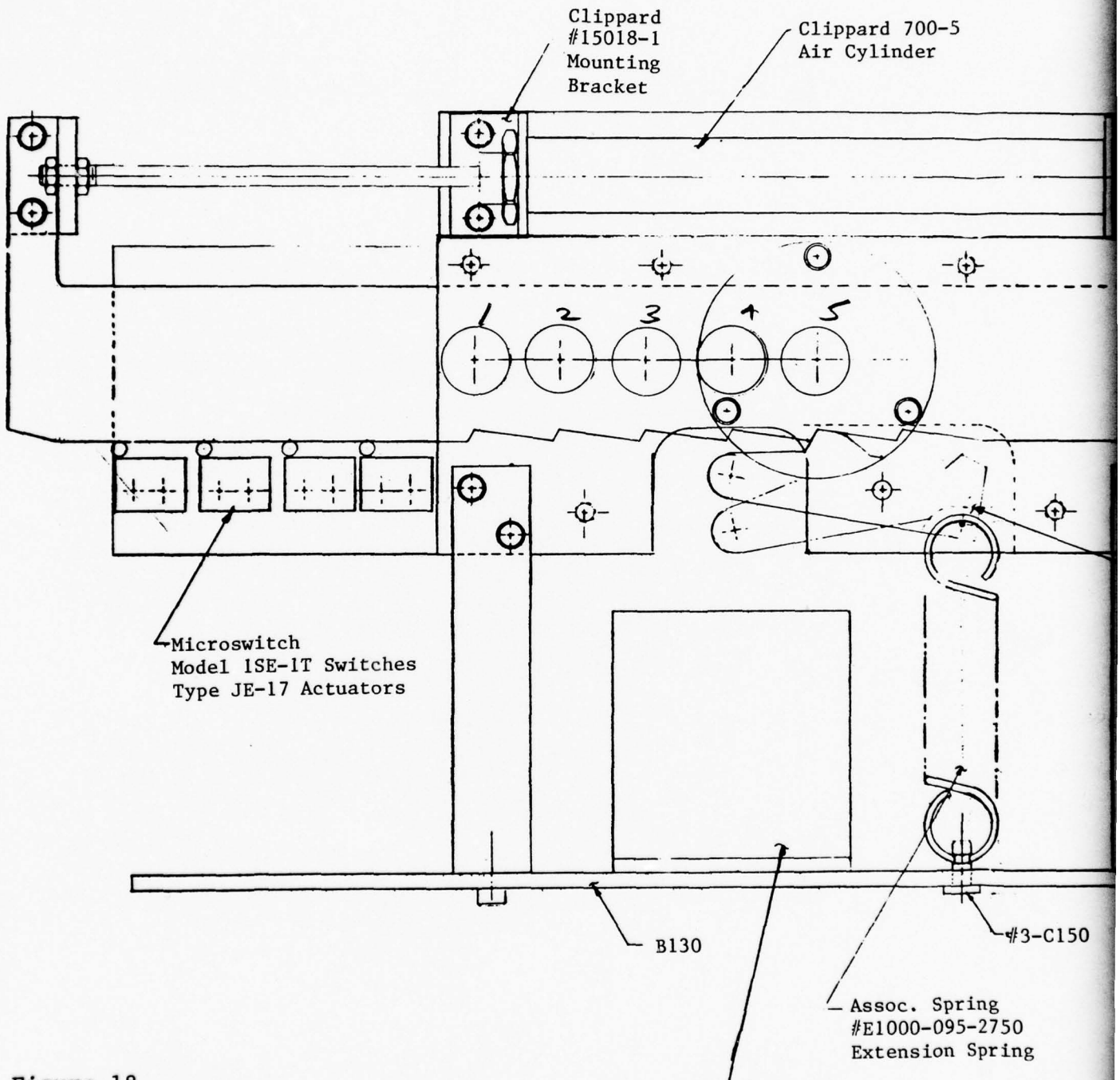
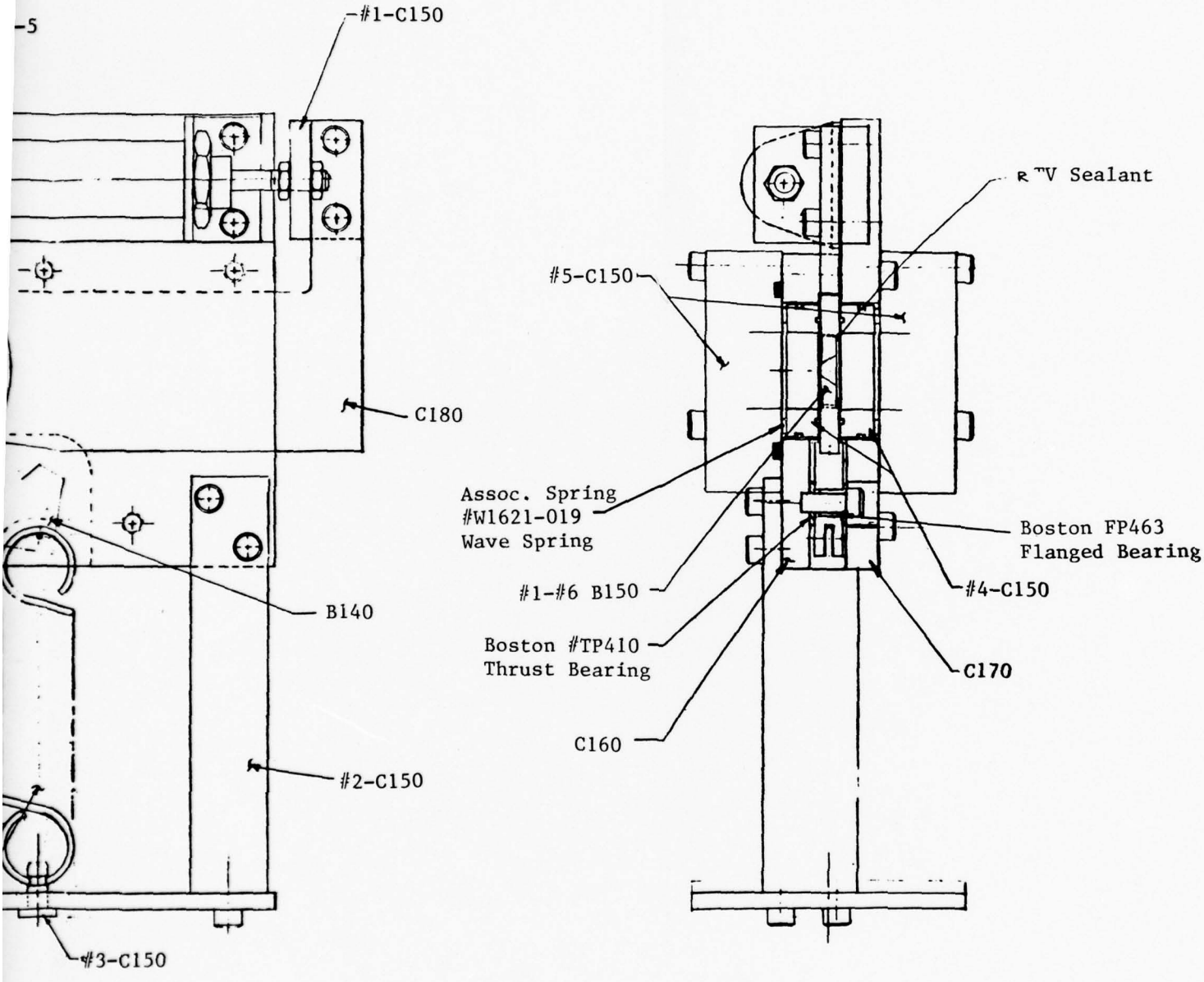


Figure 18

ORIFICE INDEXER ASSEMBLY
DRAWING



Assembly Drawing
Orifice Indexer Mechanism
Full Scale

C6352-2-200

and were reproducible to within approximately 3%. Figure 19 is a photograph of the orifice indexer assembly and displays the flow outlet side.

Design of the secondary diluter was conceptually similar to that of the primary diluter. An air supply plenum was located beneath the secondary diluter along with solenoid valves and flow restricting orifices to control the desired amount of dilution. The entire secondary diluter assembly was mounted on a plate in common with the top plate of the mass sampling turret assembly. The function of the secondary diluter was to adjust the particle concentration of the sample prior to collection within the secondary circuit.* Supply air for this diluter and the pneumatic equipment associated with the turret assemblies was tapped from the cleaned dilution air supply upstream from the pressure regulator. This secondary air supply was separately regulated to permit the necessary adjustments to obtain good operation of the turret assemblies and the secondary diluter. Figure 20 shows the assembly drawing for the secondary diluter and the extraction tube used to withdraw the secondary sample flow. The photograph in Figure 15 shows the completed unit.

2.2.6 Auxiliary Systems

The sound enclosure, air-processing unit, and the control panel used for operating the sampling system are described here. The purpose of the sound enclosure was to house and protect the particle collection equipment from the test cell environment. The air-processing unit consisted of all the equipment not contained within the sound enclosure.

The layout and construction of the sound enclosure plus the relative location of the sampling components within the enclosure is shown in Figure 21. The basic design was a

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* Especially important for the concentration limited electrical aerosol analyzer (EAA).

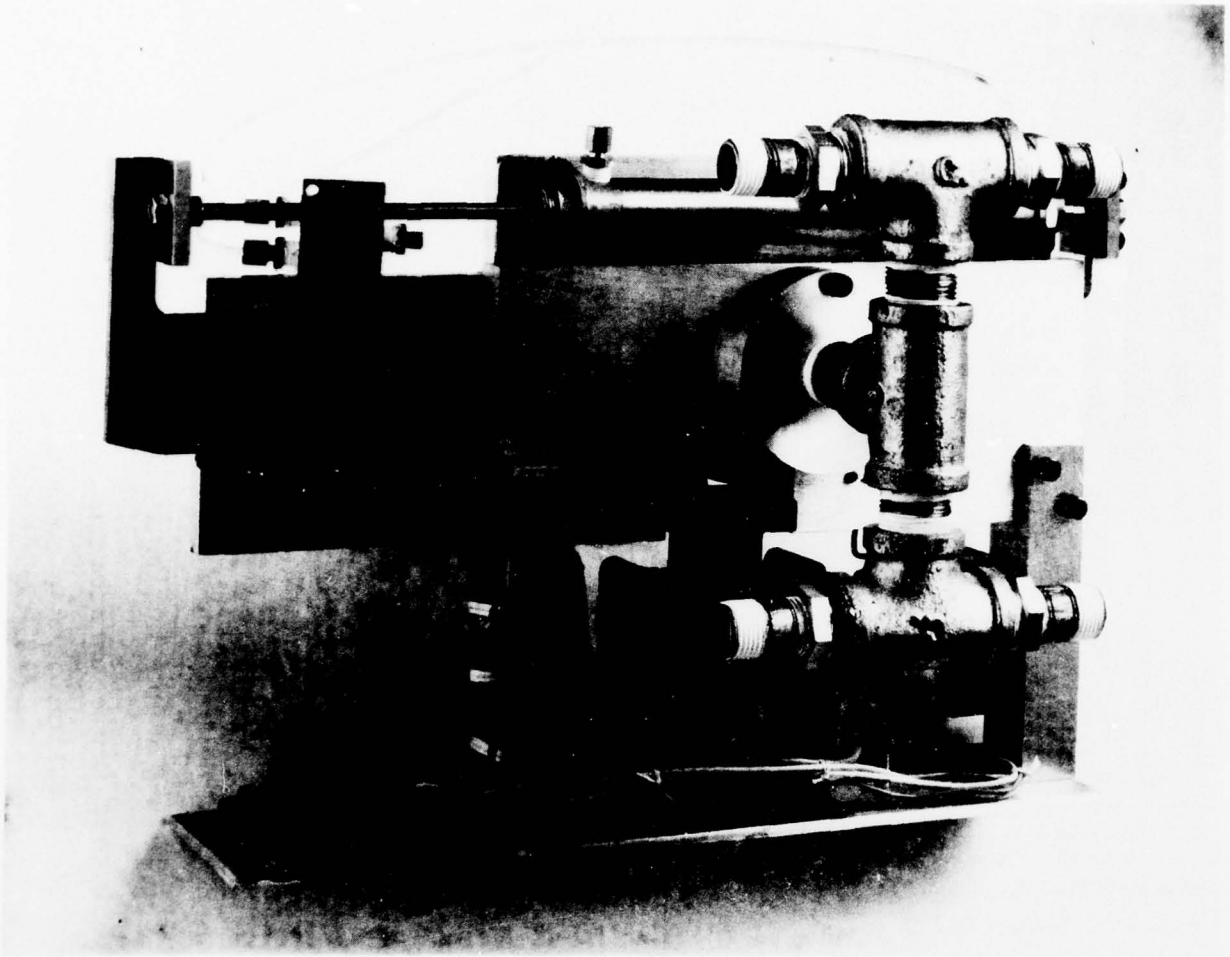

Figure 19

PHOTOGRAPH OF THE ORIFICE INDEXER FABRICATED
TO REGULATE DILUTION AIR OF PRIMARY DILUTER

(VIEW IS OUTLET SIDE)

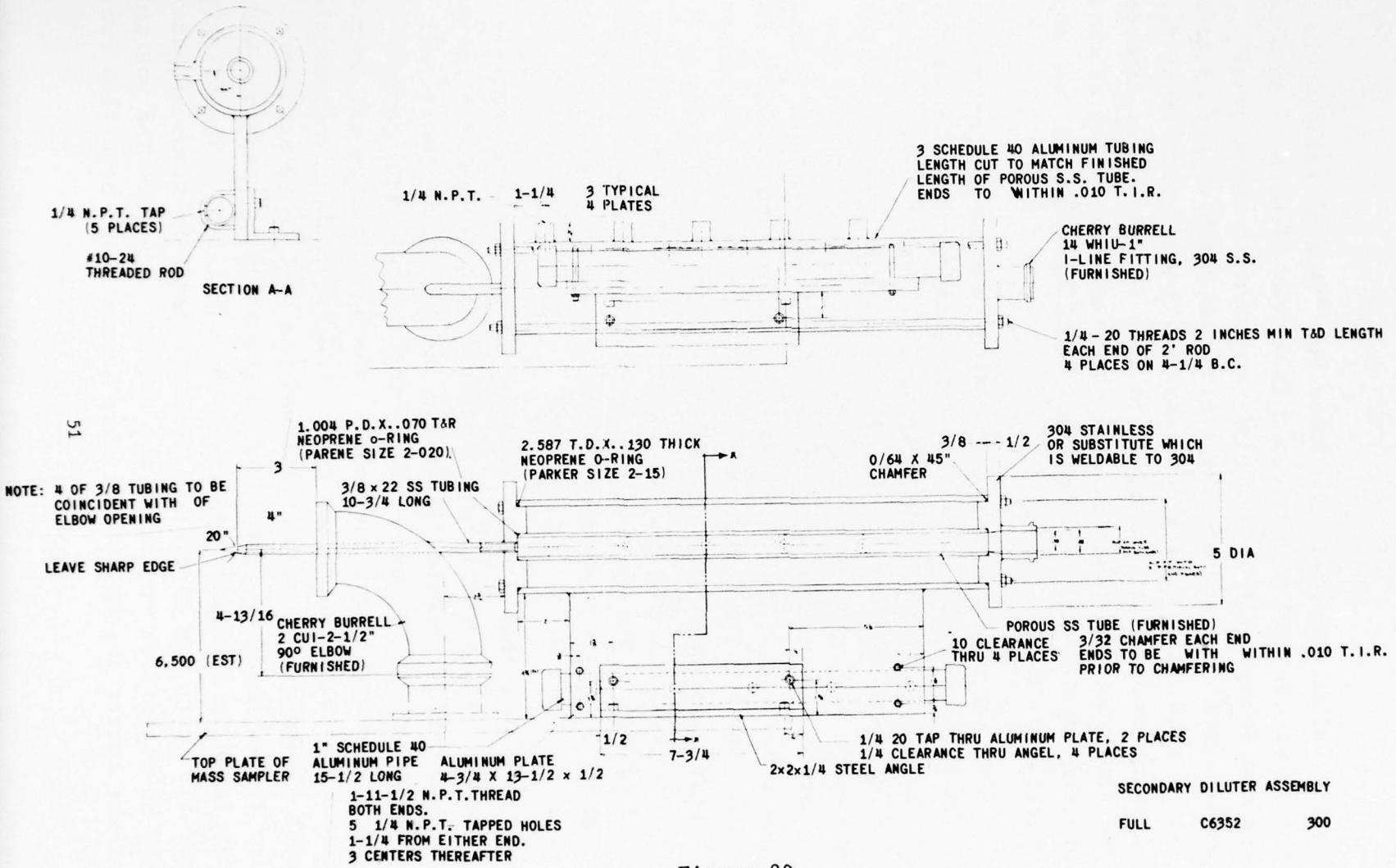

Figure 20

ASSEMBLY DRAWING OF THE SECONDARY DILUTER

double-walled box where the inner box "floats" relative to the outer box (both constructed from 3/4" plywood). Between the two boxes, 1/16" sheet lead sandwiched between equal thicknesses (2") of foam insulation comprised the sound insulating wall. The access door covered the complete front face allowing convenient admittance to each of the housed assemblies. The door also contained the sheet lead and the double thickness of foam insulation. The internal sampling equipment was approximately 900 lbs.

The air-processing unit contains numerous components as shown in Figure 22. The diluter is located along the center of the skid with the flow outlet end (2" dia.) directed toward the front of the photograph. The right-hand side is the equipment supplying the air to the diluter. The far end on this side supports the vacuum pump used in conjunction with the secondary sample circuit. The left-hand side starts with the Roots rotary vacuum pump in the foreground, a bleed valve, the flow meter (hot-wire anemometer), and finally the 1" control valve. Items not present in Figure 22 include the 2" bleed valve and the two flow dampers. The air-processing unit can be located up to 25' from the sound enclosure as all the hoses and electrical lines were this length.

All functions within the sampling system were remotely operated. All control functions were centralized at a single control panel, therefore allowing one person to control all test functions. Figure 23 shows the control panel housed within a portable carrying case. The positions on the turret assemblies were controlled by an indexing push-button, coupled with a toggle switch which allowed the seal to be kept open for turret changes. The turret plate sampling positions were displayed by indicator lights on the panel face. The dilution air flow rate was controlled from the panel by means of indexing and reset buttons operating the orifice indexer. The position of the turret assemblies, orifice indexer, and both flow control

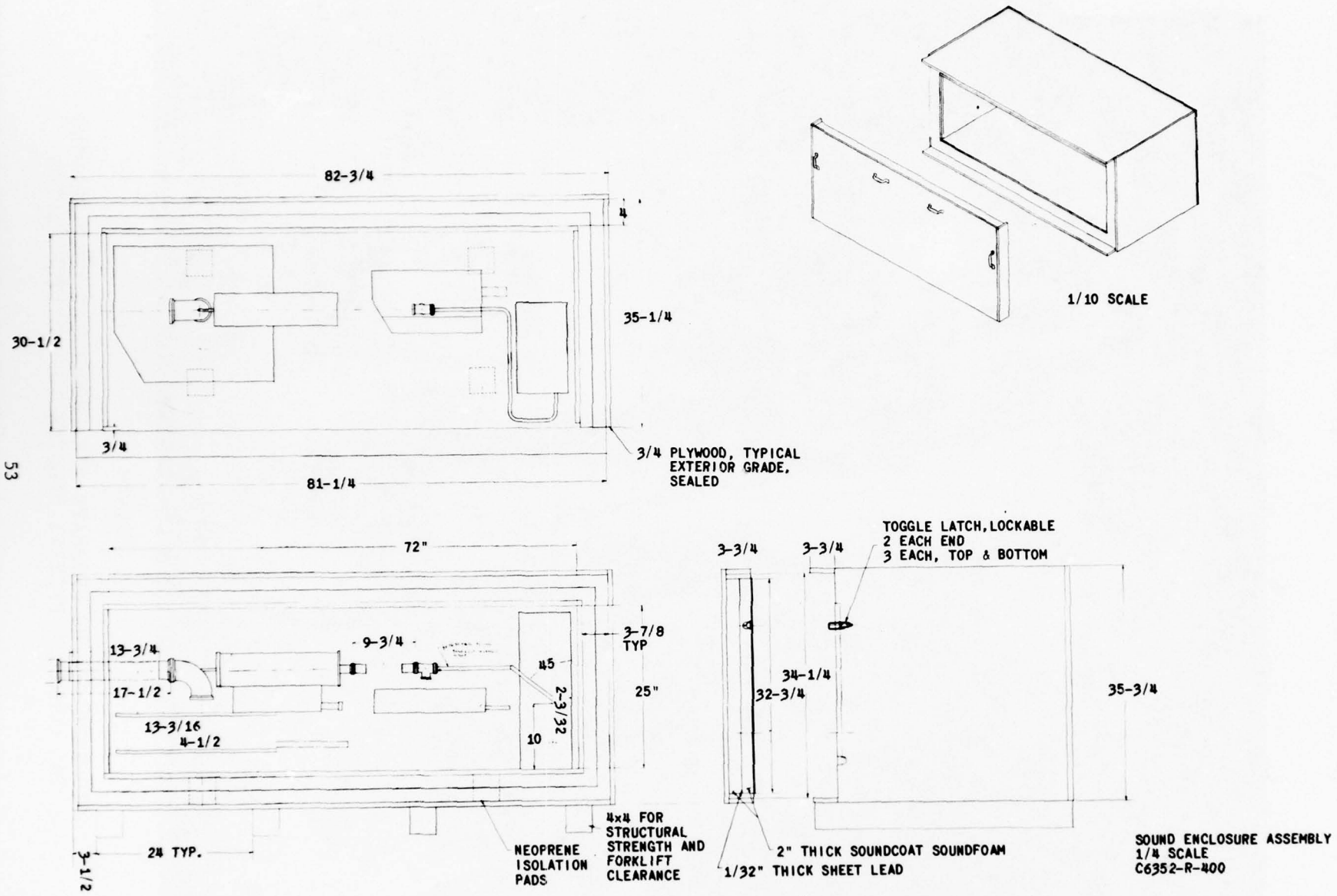

Figure 21

ASSEMBLY VIEW AND CONSTRUCTION DETAIL OF SAMPLER SOUND ENCLOSURE

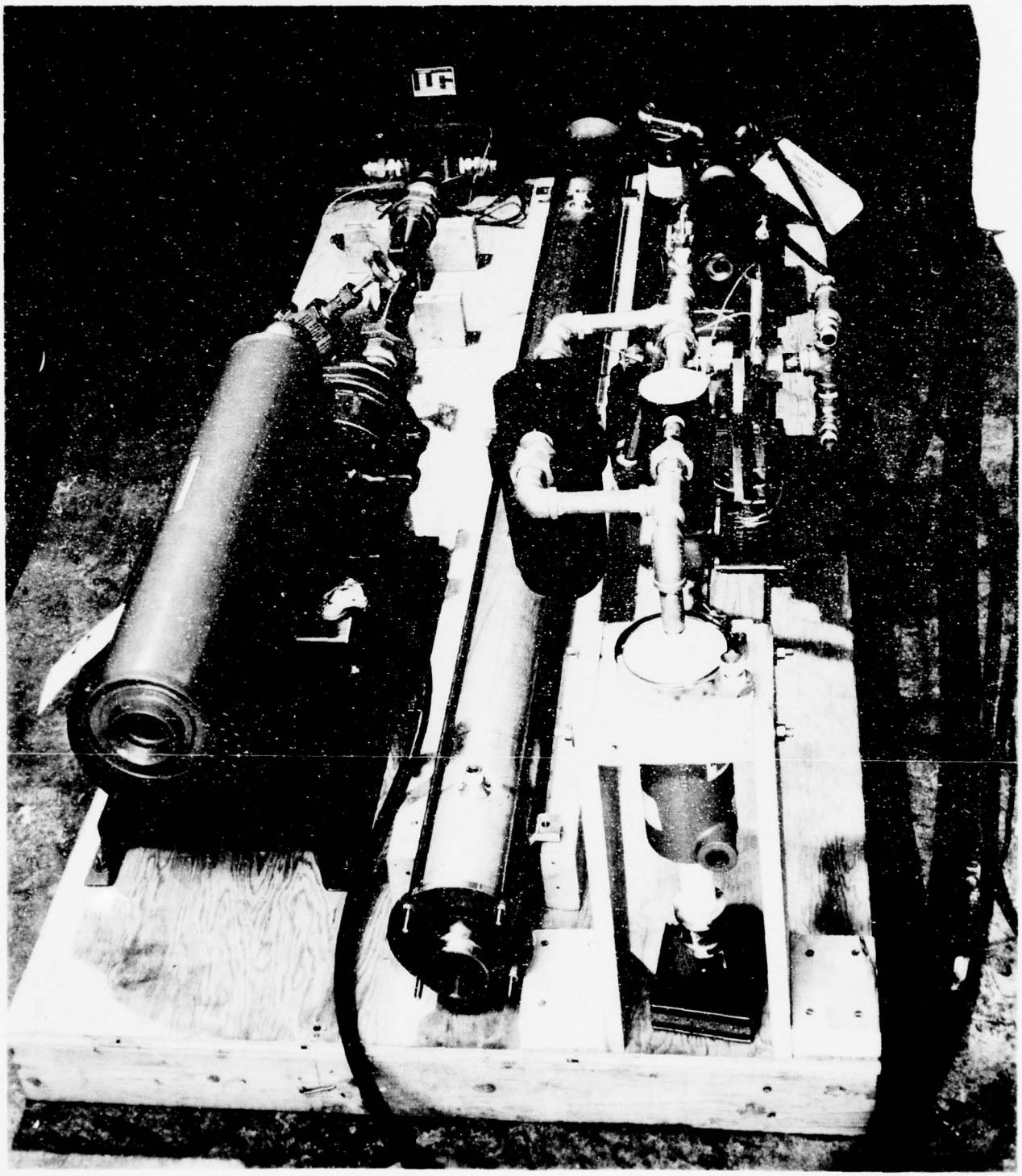

Figure 22

PHOTOGRAPH OF THE SEPARATE AIR-PROCESSING UNIT SHOWING
THE COMPLETE PRIMARY DILUTER TUBE AT THE CENTER

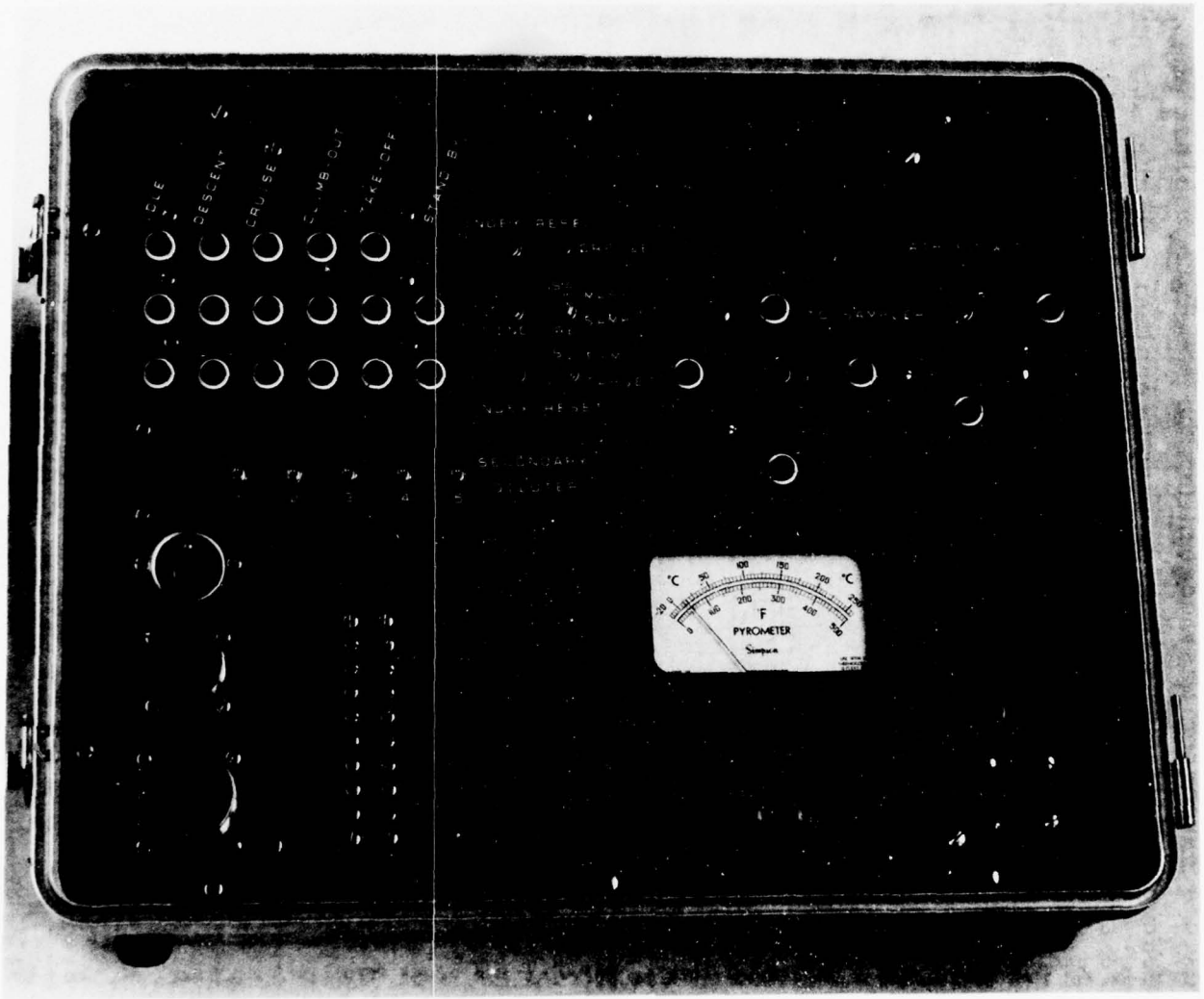

Figure 23

PHOTOGRAPH SHOWING THE SAMPLING SYSTEM'S CONTROL PANEL

valves were shown by indicator lights. Secondary dilution air was controlled by toggle switches which operated the solenoid valves. A pyrometer was located on the panel to monitor the temperatures indicated by three thermocouples: diluter air, sample temperature at mass sampling turret, and the ambient temperature within the sound enclosure. Control cables to both the sound enclosure and air-processing unit connected onto the control panel. The flow meter readout, electrical aerosol analyzer control package, flow modulating bleed valve controller, and electrical switching to both vacuum pumps were located adjacent to the control panel.

2.3 Operating Procedure

During the two sampling trips to the NAFEC engine test facility, a successful operating procedure was developed. The EAA sample was taken first, then the sample for particle analysis (EM sample),* and last the mass loading sample. The procedure used to operate the sampler is given below.

1. Before engine started, both vacuum pumps off, both turrets at stand-by, primary dilution flow on, secondary diluter off.
2. Aircraft engine started.
3. System bleed valve open.
4. Sample air flow in by-pass.
5. Secondary flow closed.
6. Mass sampling (MS)** turret in stand-by.
7. Particle analysis (EM) turret in stand-by.
8. Roots rotary pump and vacuum pump off.
9. Secondary flow to EAA.

---

* EM - electron microscope.

** MS - mass sampling filter.

10. Vacuum pump on.
11. Roots rotary pump on (EAA sample).
12. Roots rotary pump off (EAA sample complete).
13. Secondary flow to close.
14. Vacuum pump off.
15. Index MS to idle.
16. Index air flow to sample.
17. Roots rotary pump on (MS sample), adjust bleed.
18. Roots rotary pump off (MS sample complete).
19. Sample flow to by-pass.
20. Index MS turret to stand-by.
21. Index EM turret to idle.
22. Vacuum pump on.
23. Index secondary flow to EM turret.
24. Air flow to sample.
25. Roots rotary pump on (EM sample).
26. Roots rotary pump off (EM sample complete).
27. Secondary flow to close.
28. Vacuum pump off.
29. Index EM turret to stand-by.
30. Repeat, starting at Step 3, for next engine power setting.

The total time elapsed during the acquisition of five mass samples and five EM samples was about 1-3/4 hours. This corresponds to the TF-30 engine comprising the test facility at NAFEC. Depending on the particular engine, mass emission may vary, thus requiring extended or reduced sampling times.

The particle build-up on the face of the glass fiber filter for mass emission samples required the continual adjustment of the system bleed in order to maintain a constant net sample flow. Very slight adjustment was necessary at idle, while nearly continuous adjustment was mandatory at take-off.

At the lower engine power settings, isokinetic flow was achieved through the proper selection of sample flow rate. These lower power settings include: idle, approach, and cruise. As noted previously, climb-out and take-off were sampled at a fixed rate due to choking conditions at the nozzle entrance.*

Supply pressure to the diluter was maintained at 30 psig. The heaters installed on the outer manifold maintained the sample temperature above approximately 130°F. During the NAFEC tests, the actual measured sample temperature varied between 120° and 162°F and depended only on the inlet sample flow rate and its temperature. During these tests, two dilution flows were used as follows to give a more uniform dilution flow ratio:

idle and approach - 5.85 scfm

cruise, climb-out, take-off - 8.45 scfm

In securing the EM grids to the Nuclepore membrane filter, Duco cement was applied first to the filter to form a small "dot". Next, the EM grid was gently pushed into the side of the glue dot. In this way, a minimum amount of glue was used in securing the EM grid. The side of the EM grid coated with carbon was always facing upward towards the flow. In the deposit of the particles onto the grid surface, the deposition was uniform demonstrating the absence of any electrostatic effects.

Both the glass fiber and Nuclepore substrate were stored after retrieval from the turret plate assemblies. The glass fiber filters were placed in pyrex petrie dishes. The Nuclepore

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* See Reference 1.

membrane filters and EM grids were stored in plastic holders until analysis was performed.

3. TEST RESULTS FROM SAMPLING SYSTEM

During the months of February and June of 1977, two separate trips were made to the NAFEC test facility in Atlantic City, New Jersey. The purpose of these trips was to perform final adjustments to and make performance evaluations of the sampling system. At NAFEC, the engine availability was continuous as the entire test facility is dedicated to experimental operations. This enabled the IITRI sampling crew to concentrate their efforts on the sampling system and thus enable the engine operation time to be most effective.

The data obtained includes the mass concentration of the exhaust stream from the engine and the characterization of the particulate material. Characterization includes the particle size distribution, the variation of shape with particle size, and particle morphology. The data generated thus far by the sampling system includes only the NAFEC testing using the TF-30 turbine engine. The purpose of the data obtained at NAFEC was to determine the reliability of the sampler's performance in making particle measurements and to develop an analysis protocol at IITRI for the particle characterization. This section of the report discusses the performance of the sampling system in terms of the data obtained.

3.1 Exhaust Particulate Mass Concentration

The particulate mass concentration was determined through differential gravimetric analysis of the glass fiber filters manipulated by the mass sampling turret. The filters were weighed before and after sample collection and corrected for shifts in weight due to hygroscopic effects with control filters. Table 4 lists the numerical data and the sampling system operating conditions. Test numbers 5, 6, and 7 were conducted during the first trip to NAFEC in February. Test

Table 4

MASS LOADING SAMPLE DATA

Test #	Engine Power Setting	Net Wt. Collected* (gm)	Sample Time (min)	Sample Flow Rate (m^3/min)	Exhaust Part. Mass Conc. (gm/std. m^3)	SAE*** Smoke #
5	idle	0.0067	15	0.0396	0.0113	42.3
(2/16/77)	approach	0.0219	10	0.0622	0.0352	67.3
	cruise	0.0413	10	0.0736	0.0561	82.2
	climb-out	0.0488	10	0.0792	0.0616	81.0
	take-off	0.0259	5	0.0991	0.0597**	79.8
6	idle	0.0046	15	0.0396	0.0077	33.0
(2/17/77)	approach	0.0229	10	0.0622	0.0368	64.9
	cruise	0.0309	7	0.0736	0.0600	77.1
	climb-out	0.0261	5	0.0792	0.0659	79.0
	take-off	0.0175	3	0.0792	0.0841**	82.1
7	idle	0.0061	15	0.0396	0.0103	39.1
(2/18/77)	approach	0.0168	7	0.0622	0.0385	66.0
	cruise	0.0249	5	0.0736	0.0677	77.0
	climb-out	0.0198	3	0.0792	0.0833	77.5
	take-off	0.0139	2	0.0792	0.0101**	81.3
8	idle	0.0100	15	0.0396	0.0168	32.9
(6/08/77)	approach	0.0147	7	0.0622	0.0337	64.6
	cruise	0.0202	5	0.0736	0.0549	71.1
	climb-out	0.0116	3	0.0792	0.0489	76.2
	take-off	0.0108	2	0.0792	0.0780**	76.6
9	cruise	0.0141	4	0.0736	0.0479	72.0
(6/09/77)	cruise	0.0145	4	0.0736	0.0492	70.8
	cruise	0.0142	4	0.0736	0.0482	70.4
	cruise	0.0141	4	0.0736	0.0479	--
	cruise	0.0143	4	0.0736	0.0555**	--
10	idle	0.0042	15	0.0396	0.00706	33.2
(6/10/77)	approach	0.0097	5	0.0622	0.0311	65.8
	cruise	0.0161	4	0.0736	0.0547	71.2
	climb-out	0.0124	3	0.0792	0.0521	71.3
	take-off	0.0102	2	0.0792	0.0735**	--

* Net sample weight corrected for changes in relative humidity through control filters.

** Data corrected for anisokinetic flow on velocity basis.

*** Per SAE ARP 1179

numbers 8, 9, and 10 correspond to the June sampling trip to NAFEC. Test numbers 1 through 4 were preliminary tests concentrating on adjusting the sampling system for optimum results. The two right-most columns give the resultant exhaust particulate mass concentration and the corresponding SAE smoke number [2]. The determination of smoke number was performed by the NAFEC test cell personnel. Smoke sample was taken midway between the center and bottom of the exhaust nozzle.

Figure 24 is a plot of the mass concentration data against the engine power setting.* This plot is useful in analyzing the data because any other engine parameter would have basically the same effect -- spreading the mass emission data in a consistent manner. As expected, with increasing engine thrust or power level, the mass concentration of the exhaust particles (g/std. m^3)** also increases. The range is about 0.01 g/m^3 at idle to approximately 0.08 g/m^3 at take-off.

Also, note that the spread in the data is greater at the higher power levels in contrast to the lower power levels. To ascertain whether this was artificially generated by the sampling system, test number 9 was conducted at the same engine power setting. As the data indicates, the mass concentration data varies only $\pm$ 2% and is considerably less than the full spread among the cruise data. However, tests 5, 6, and 7 were conducted under less favorable conditions than the later tests because system flow leaks were a definite possibility. Restricting the data to only tests 8 and 10 suggests a significant reduction in data spread implying that the engine at a particular power setting is consistent in terms of particulate emission. This conclusion is tentative since strong confidence can only be placed in three (8, 9, and 10) data sets. More

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* To obtain total mass emission rate, multiply mass concentration by engine air flow rate.

** Standard conditions: T = 59.7°F and P = 14.696 psia.

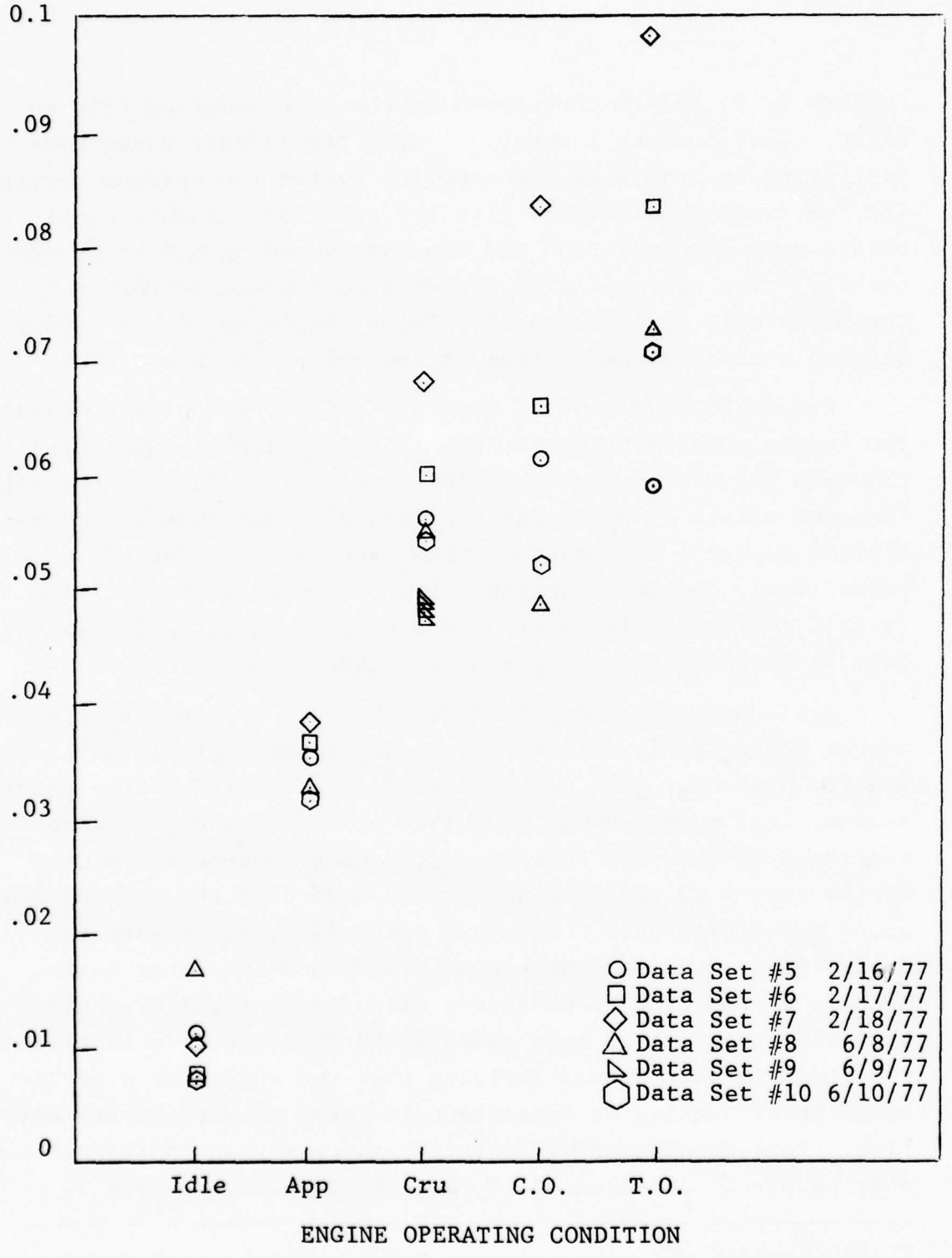

Figure 24

MASS LOADING VERSUS ENGINE POWER SETTING

importantly and in terms of this program, the sampling system has demonstrated the capability of measuring exhaust particulate concentration generated by an aircraft turbine engine.

In contrast to the mass concentration data generated by the IITRI sampling system, the smoke number data is observed (Figure 25) as displaying less scatter when reviewing all the IITRI data. However, if restricted to the last three tests, the scatter appears to be comparable. Figure 26 plots the smoke number against the mass concentration. Note that for mass concentrations above approximately 0.5 g/m^3, the smoke number is no longer sensitive to changes in mass concentration. The explanation for this is complex and probably associated with the shift in sensitivity of the reflectance measurement with greyness of the particulate deposit. As one passes the cruise power setting, the amount of reflectance on the sample does not change as much.

It must be kept in mind that the objectives of both measurements are different. With the smoke number, the overall compliance of an engine relative to exhaust "visibility" is the goal. With the mass concentration measurement, the total mass emission rate for the engine is the goal. Hence, each technique is well suited to their specific requirements and not necessarily equivalent in terms of engine parameters.

3.2 Exhaust Particle Characterization

The exhaust particle characterization was performed through analysis of the samples obtained from the smaller turret assembly located in the secondary sample flow loop. This secondary circuit was specially designed to produce particulate samples suitable for particle characterization. The data obtained thus far supports the reliability of the sampling system and is based on the work performed at NAFEC.

For the determination of particle size, both the microscopic analysis of the EM grids and the EAA size spectra

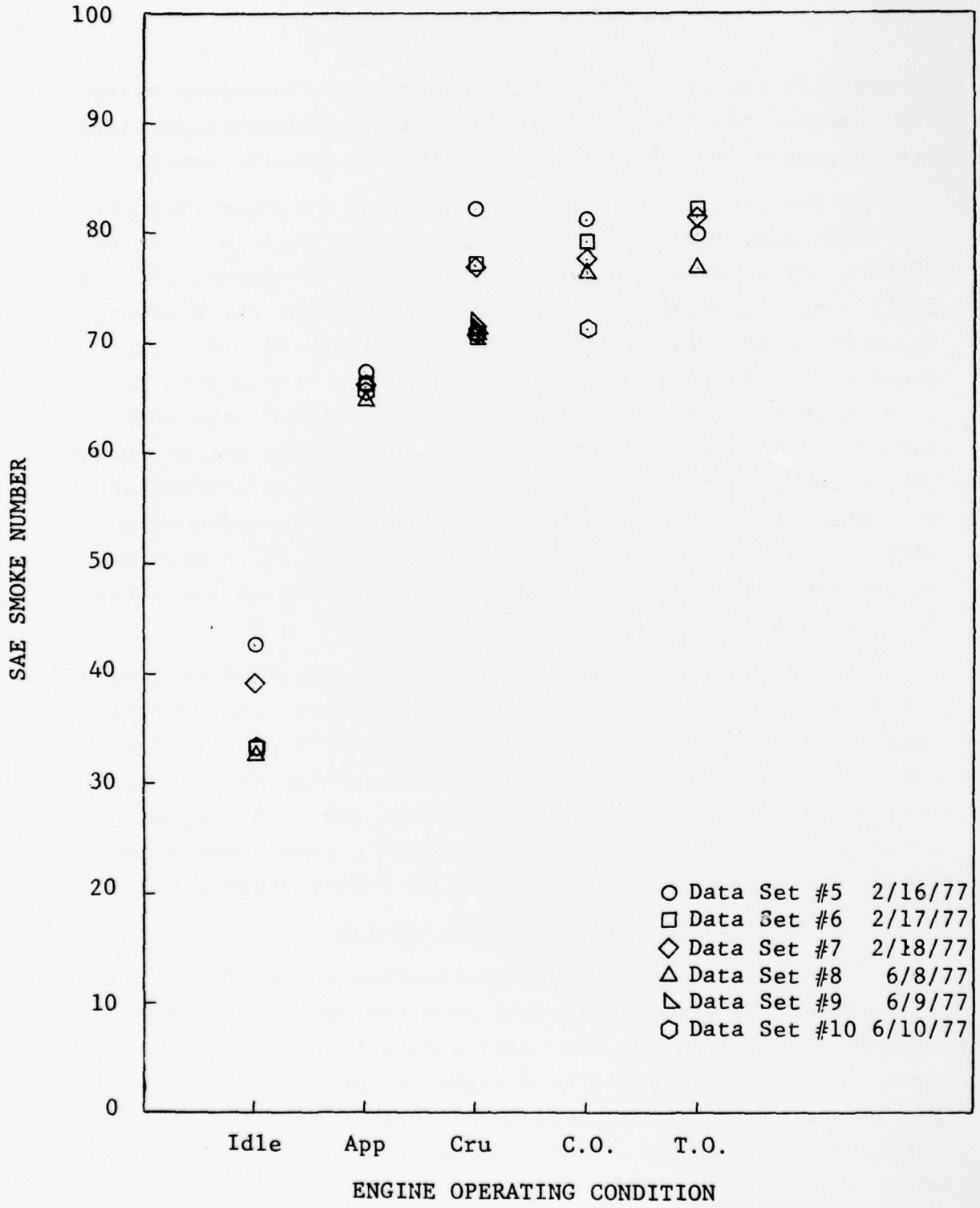

Figure 25

SAE SMOKE NUMBER VERSUS ENGINE POWER SETTING

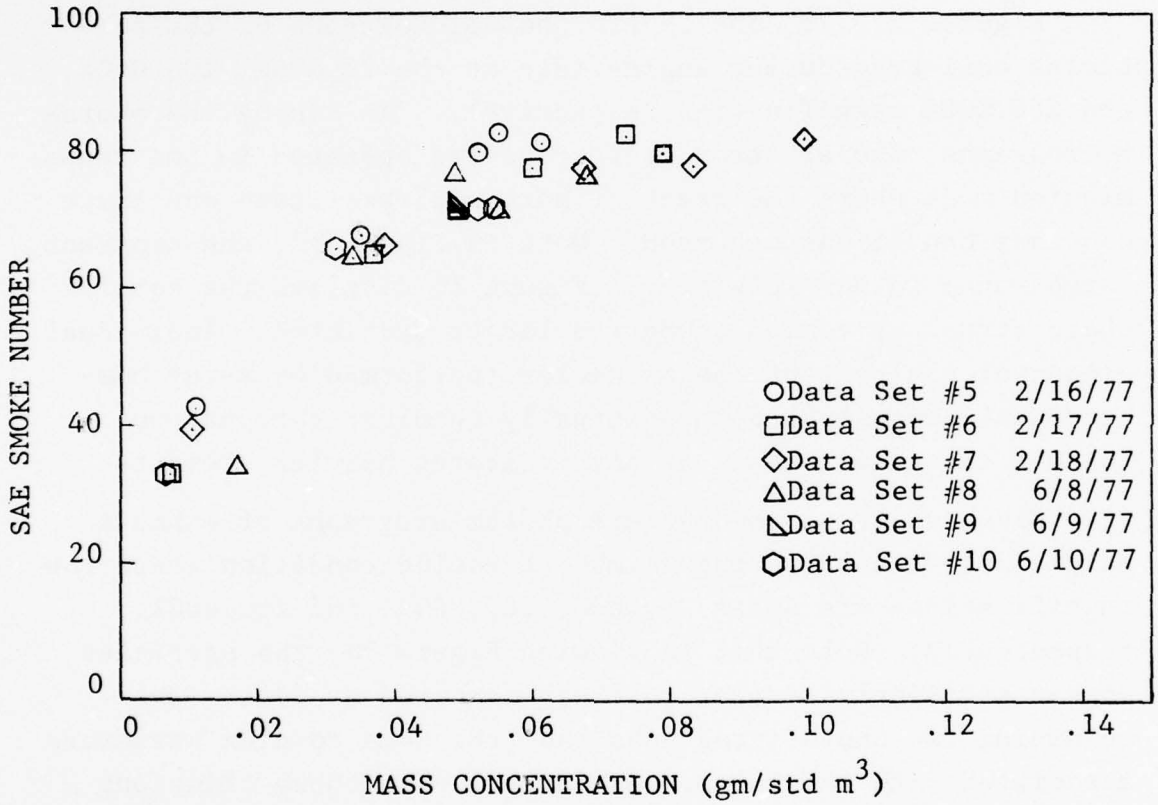

Figure 26

SAE SMOKE NUMBER VERSUS MEASURED MASS LOADING

contributed to the generation of particle size distributions. However, prior to the presentation of this data, photomicrographs are presented displaying typical particles observed at representative engine power settings during both sampling trips to NAFEC.

Figures 27, 28, and 29 are photomicrographs of the particles collected during engine idle at the 25,000X, 100,000X, and 250,000X magnification respectively. In taking the photomicrographs, the electron microscope was operated in the transmission mode where the greatest particle resolution and image contrast conditions occurred. Note in Figure 27, the apparent large range in particle size. Figure 28 displays the complex chain structure common among the larger particles. Individual elemental analysis of the particles (performed by x-ray bombardment) demonstrated the virtually complete carbonaceous content from the absence of any indicated heavier elements.

Figures 30, 31, and 32 are photomicrographs of exhaust particles obtained at the climb-out engine condition where the magnifications are again 25,000X, 100,000X, and 250,000X, respectively. Note that in viewing Figure 30, the particles appear strikingly similar to those captured at idle. The remaining two photomicrographs show the same complex structure associated with the larger particles. Both these climb-out and idle samples were obtained on February 17, 1977.

The sample set obtained on June 10, 1977 was characterized utilizing the electron microscope. The transmission mode was used where the particles were directly sized. Figure 33 shows the results plotted on a cumulative basis by count. An "equivalent sphere"* was used to characterize the irregular

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* Equivalent sphere diameter is that diameter where the spherical volume equals the physical volume of the particle. Here, the investigator estimated the equivalent spherical diameter by "simple observation".

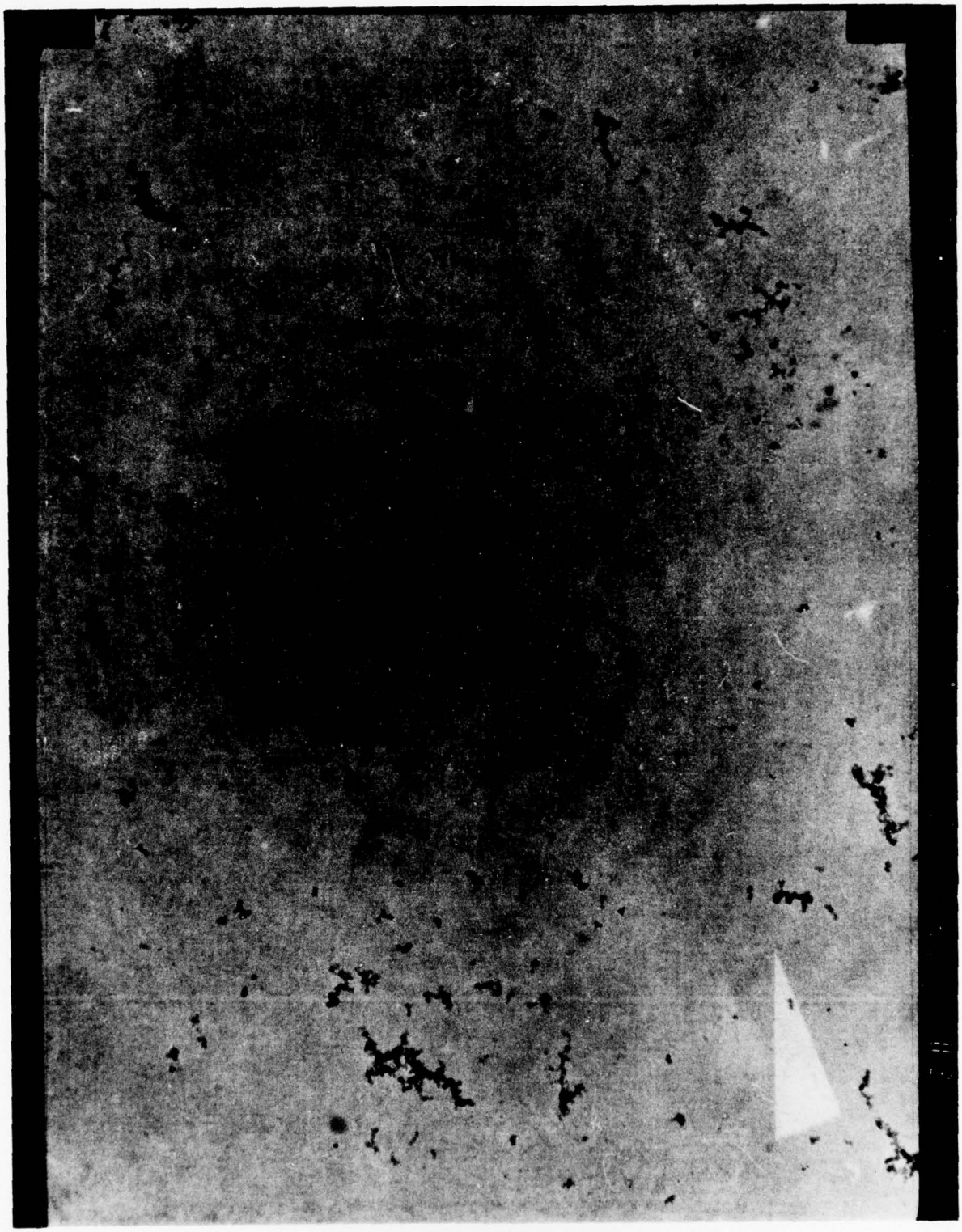

Figure 27

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT ENGINE IDLE ON 2/17/77 (MAGNIFICATION = 25,000X)

Figure 28

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT ENGINE IDLE ON 2/17/77 (MAGNIFICATION = 100,000X)

Figure 29

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT ENGINE IDLE ON 2/17/77 (MAGNIFICATION = 250,000X)

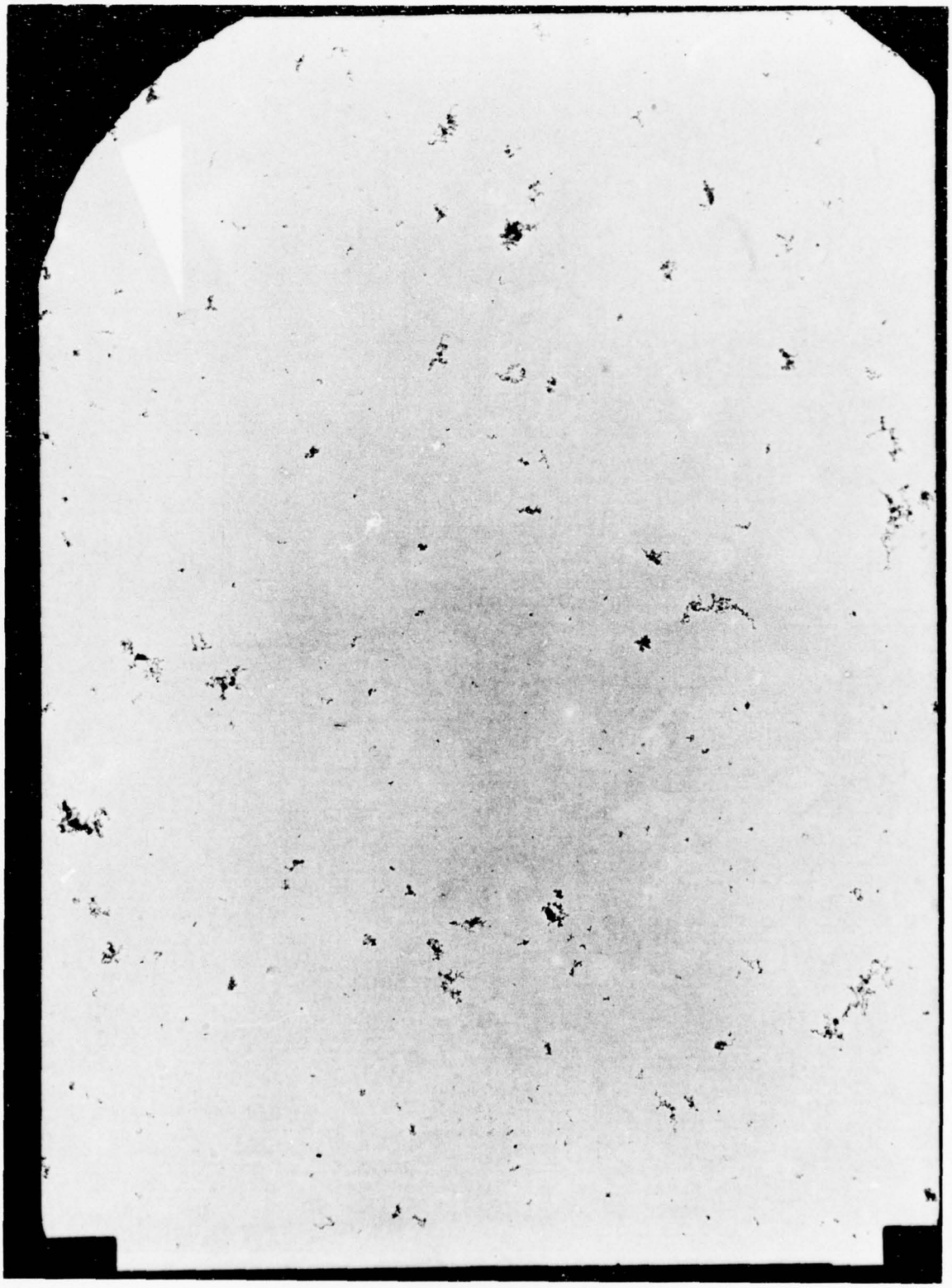

Figure 30

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT CLIMB-OUT ON 2/17/77 (MAGNIFICATION = 25,000X)

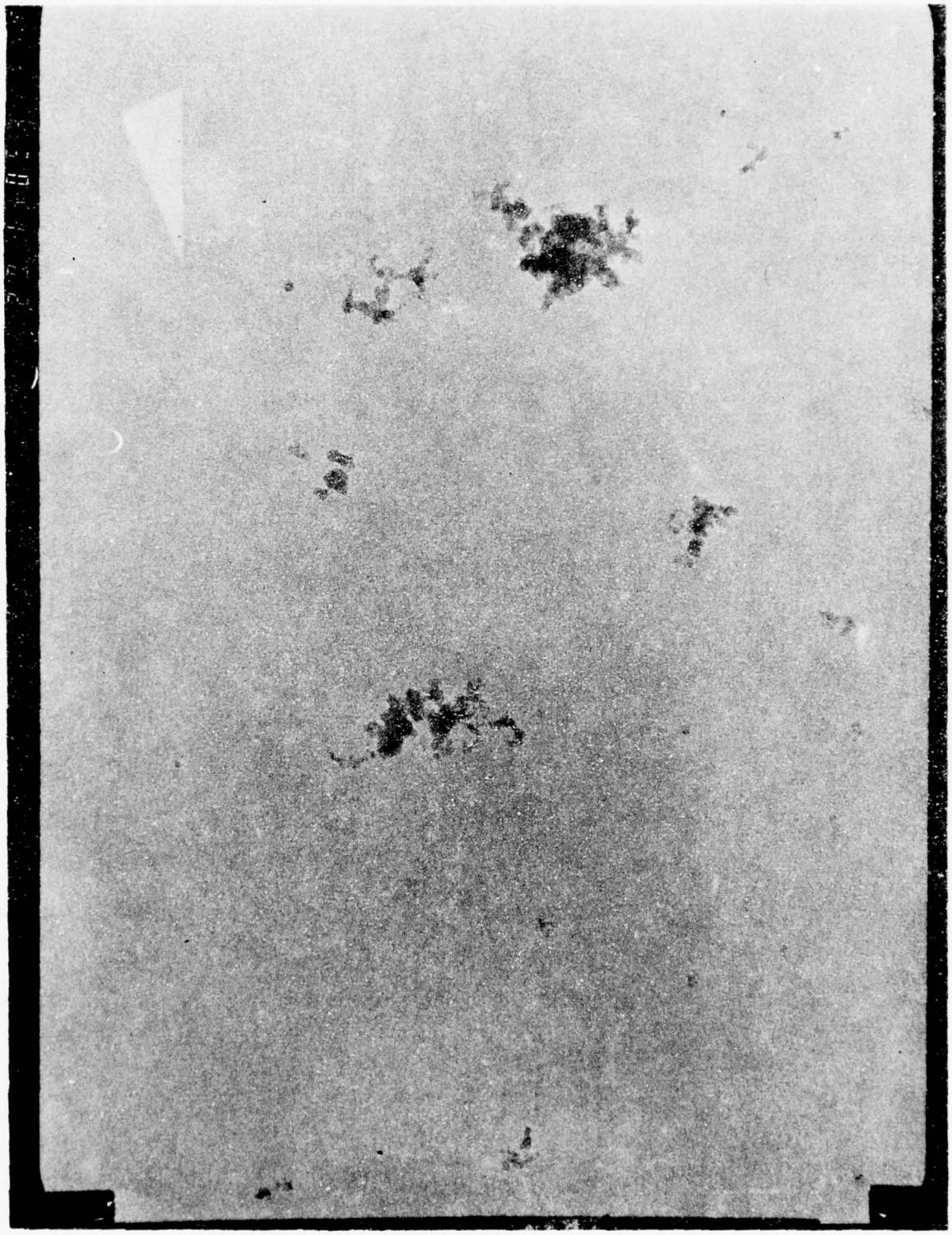

Figure 31

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT CLIMB-OUT ON 2/17/77 (MAGNIFICATION = 100,000X)

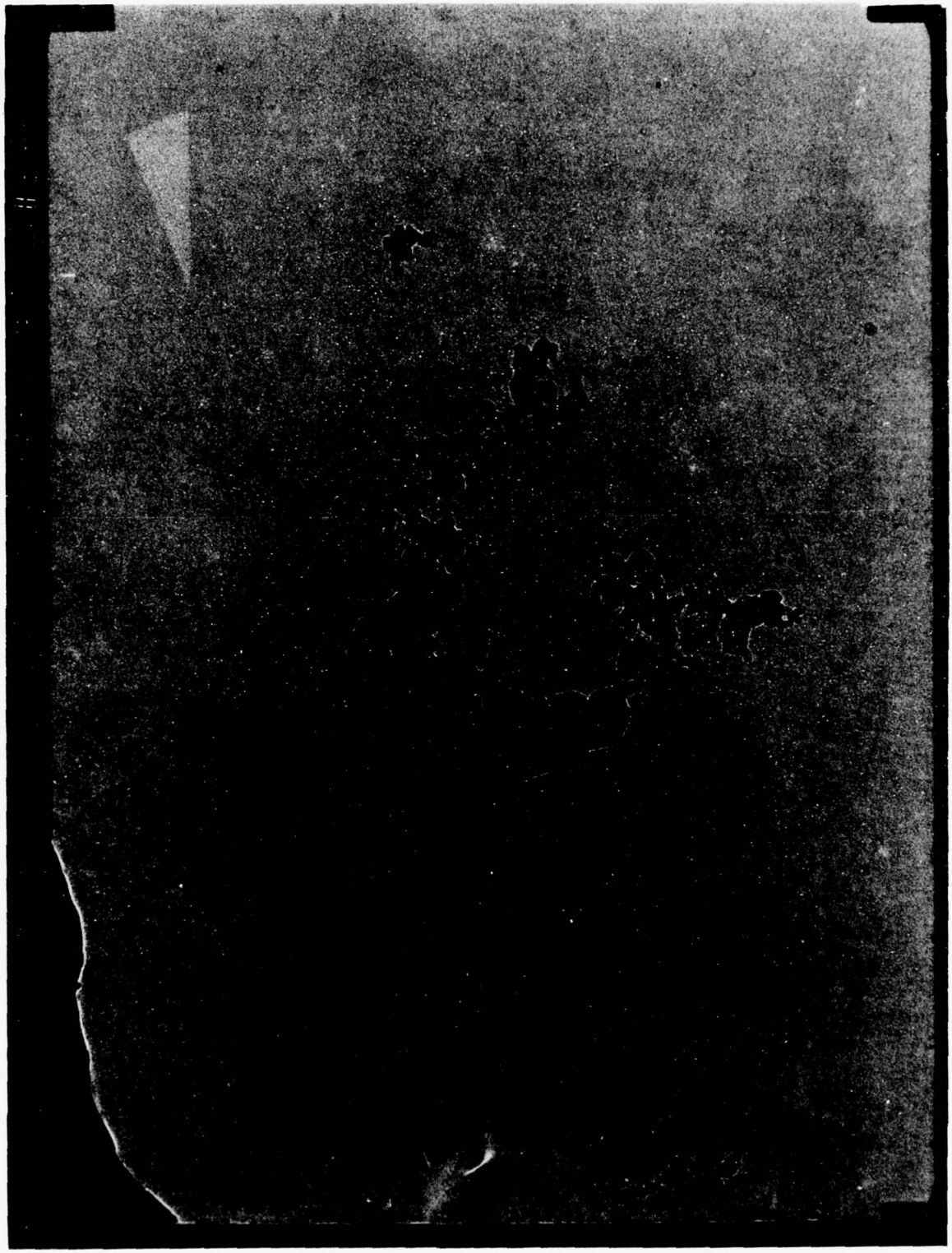

Figure 32

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT CLIMB-OUT ON 2/17/77 (MAGNIFICATION = 250,000X)

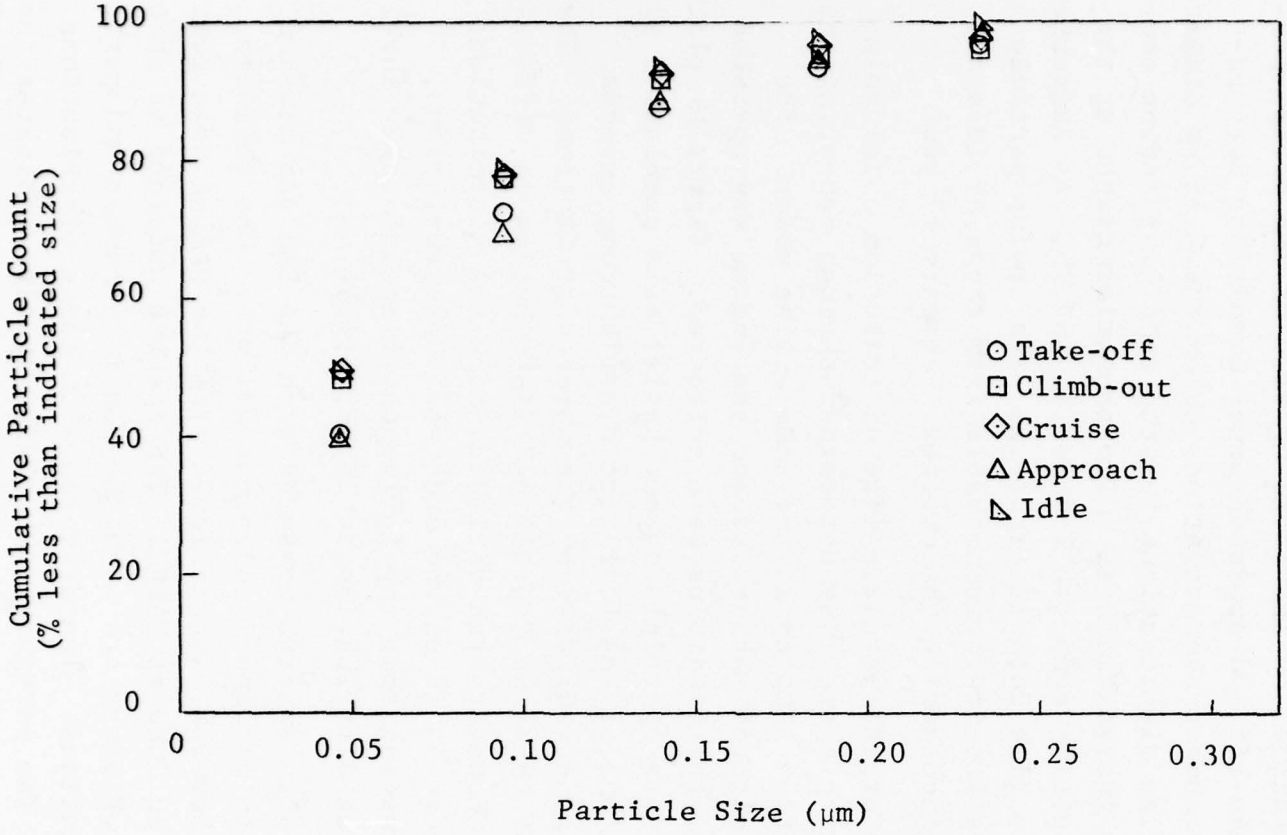

Figure 33

SIZE DISTRIBUTION FOR EXHAUST PARTICLES AT VARYING ENGINE POWER SETTING (TF-30) TAKEN JUNE 10, 1977

shape of the particles. In the analysis, all the aggregates were treated as single particles as their ultimate fate in the atmosphere hinges on the settling rate of the entire particle. The take-off and approach power conditions have reduced particle number concentrations below the 0.15 μm diameter. The particle size distributions for the remaining engine conditions varies insignificantly. Two photomicrographs at the cruise power setting comprise Figures 34 and 35. As suggested by the particle size data in Figure 33, the cruise particle characteristics are indistinguishable from those of idle and climb-out obtained during the earlier, February 17 test.

Precision of the particle size distribution obtainable with the sampling system was determined through repeating the collection of four samples at the same engine power. The engine power selected was cruise and the engine was operated continuously as these samples were collected. Figure 36 plots the resulting data (particle number basis) as a cumulative size distribution. One of the four size distributions extends beyond the range established by the three distributions. The significance of this one "out-lying" distribution is difficult to ascertain. However, the variance among the distributions plotted in Figure 33 is on the order of these variations, therefore suggesting that the influence of engine power level on particle size distribution is imperceptible.

Particle size spectra measured with the EAA was difficult to obtain due to continued equipment failure. One reliable size spectra, however, was achieved with the EAA at idle during an early test in June at NAFEC. The spectra obtained is shown in Figure 37. Plotted are both the particle number and particle volume distributions. The difference in these distributions is important. The particle number distribution indicates that the majority of particles are less than 0.0075 μm in diameter -- a peak or maximum concentration is not present. In contrast,

Figure 34

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT ENGINE CRUISE ON 6/10/77 (MAGNIFICATION = 10,000X)

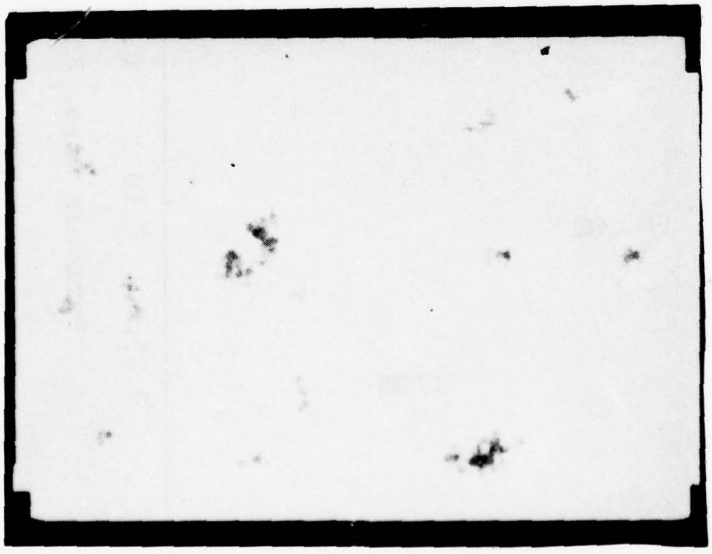

Figure 35

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES GENERATED AT ENGINE CRUISE ON 6/10/77 (MAGNIFICATION = 26,000X)

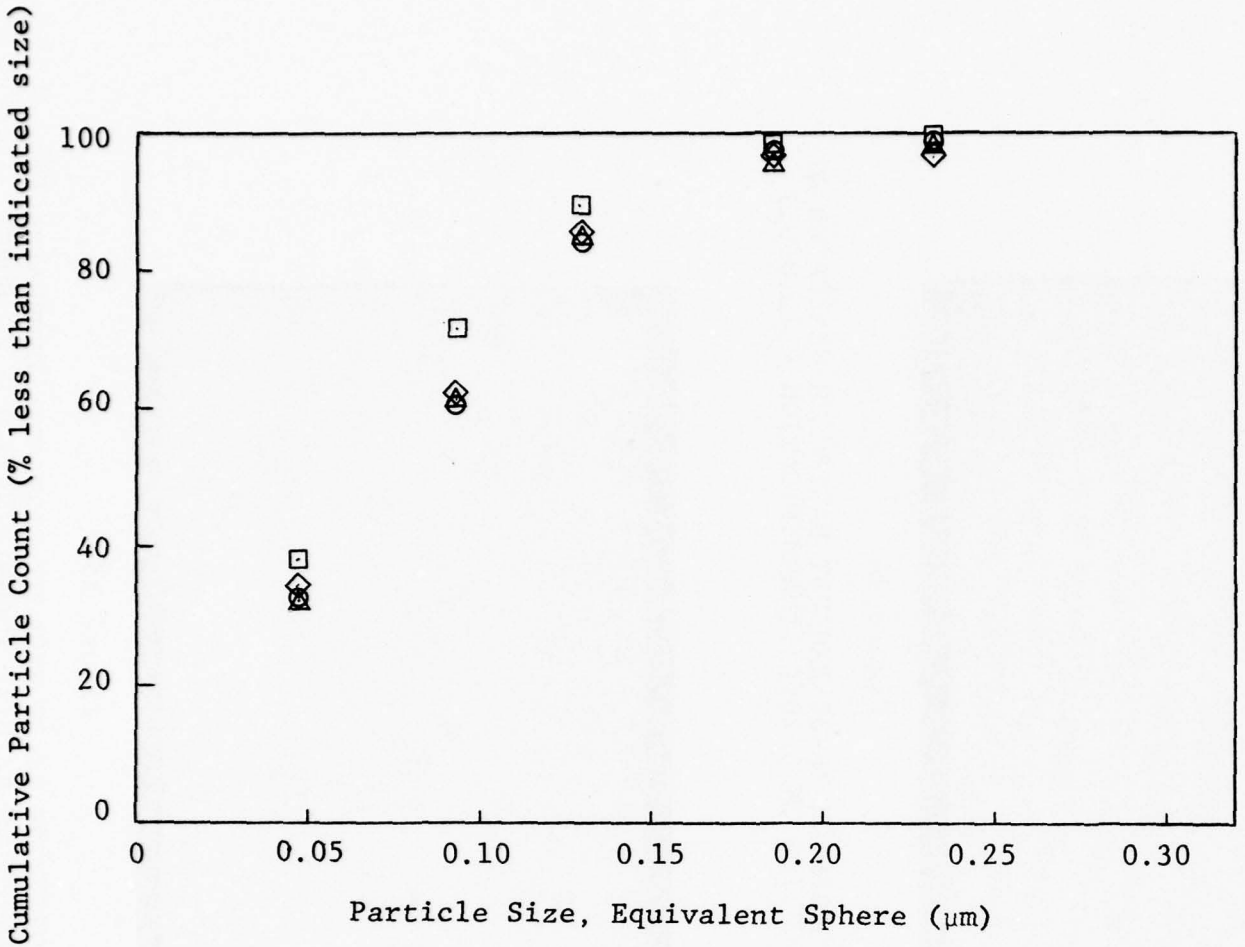

Figure 36

SIZE DISTRIBUTION FOR EXHAUST PARTICLES AT CRUISE POWER SETTING (TF-30)
TAKEN JUNE 9, 1977 SHOWING REPEATABILITY (EM)

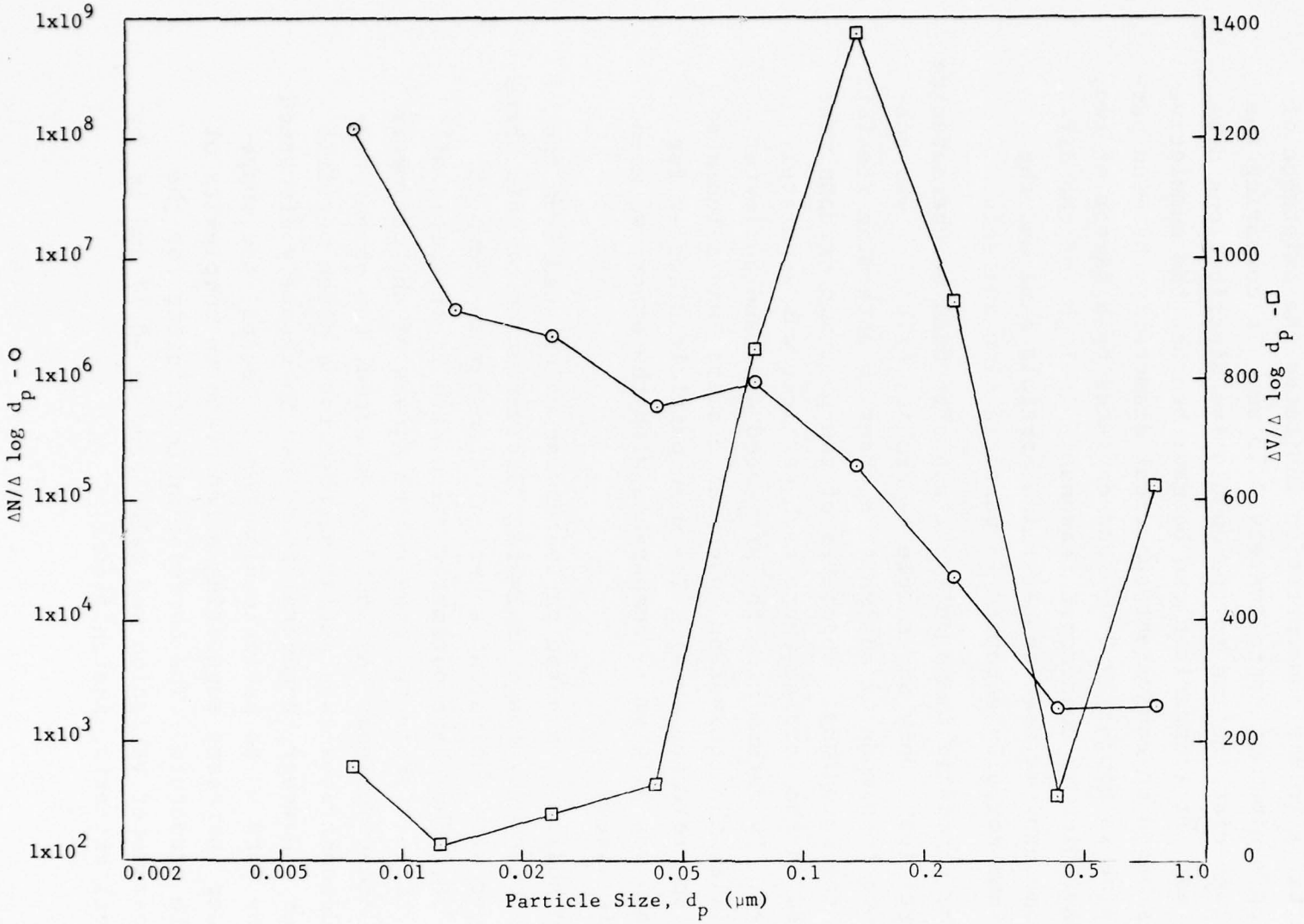

Figure 37

PARTICLE SIZE DISTRIBUTION BY NUMBER AND VOLUME AS MEASURED BY THE ELECTRICAL MOBILITY ANALYZER AT THE IDLE POWER

the particle volume concentration indicates the existence of a strong maximum at approximately 0.13 μm. In comparing the EAA volume distribution to the cumulative distributions discussed earlier (comparison can be made because the cumulative data is based on equivalent spherical diameter), the mean particle size is roughly 0.06 -- and deviates by a factor of two. This deviation is considered reasonable in light of the different mechanisms used to determine particle size and the variations normally accepted in particle size analysis.

The automatic image analyzer was also used to characterize the particles. Only one sample -- cruise, 6/10/77 - was subjected to this mode of analysis in order to determine feasibility of the technique. Negatives of the photomicrographs were analyzed on the machine where each particle was separately measured. By determining the projected area and perimeter of a particle, the equivalent spherical diameter was calculated (based on projected area). The mean particle diameter for this data was 0.14 μm -- comparable with the other two mean particle sizes.

In addition, a shape parameter was calculated from the data generated by image analysis. The variation of this shape parameter with equivalent spherical diameter is shown in Figure 38. The shape parameter calculated is the ratio of the particle's projected area to the square of the perimeter and is dimensionless. As would be expected, the shape parameter demonstrates substantial scatter for a given particle diameter. However, a general trend can be visually discerned from the data -- as particle diameter decreases, the shape parameter increases suggesting a reduction in complexity of particle structure. The correlation coefficient for the shape parameter variation was calculated as -0.17 and is, by stastical criteria, insignificant.

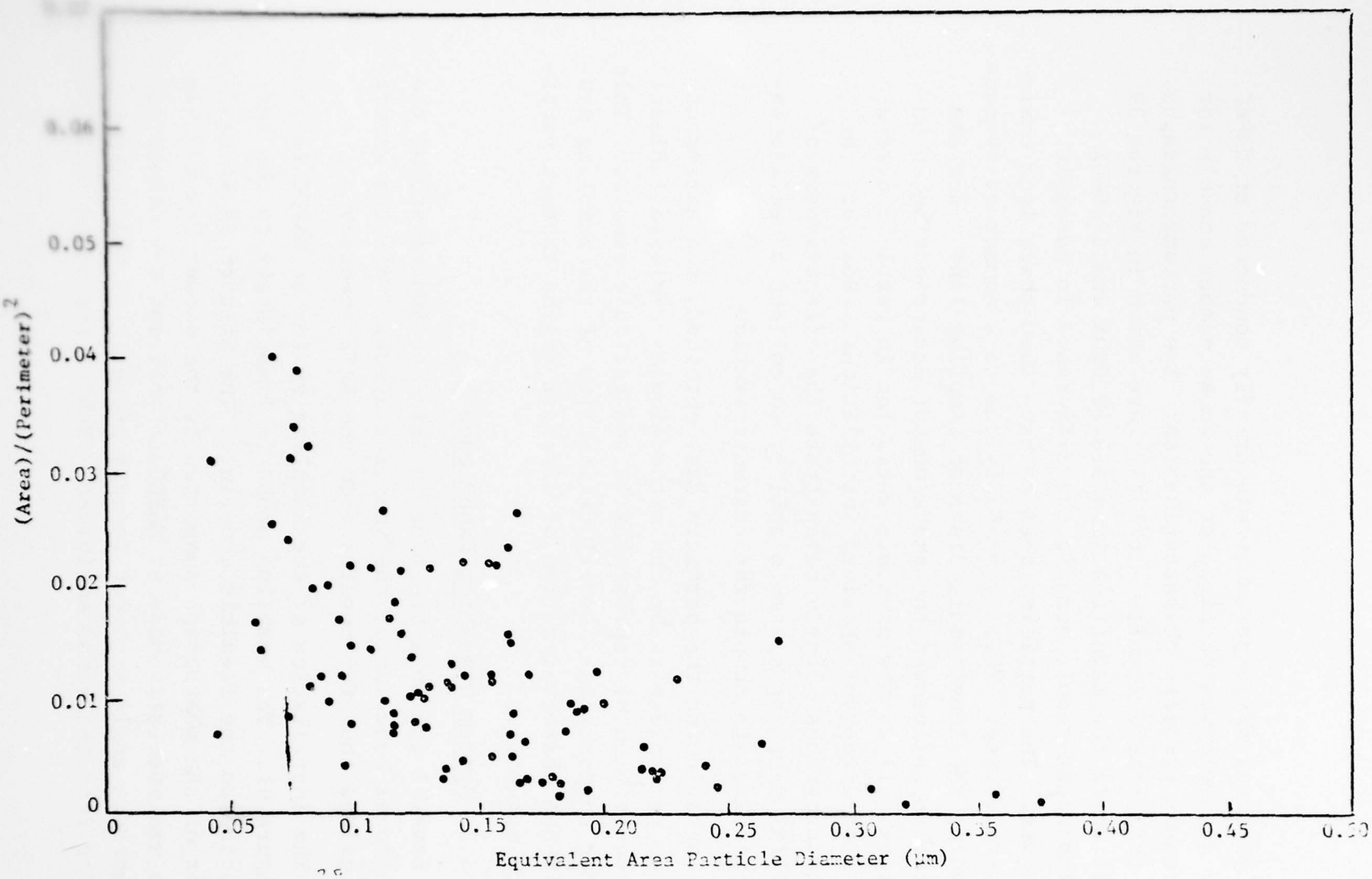

Figure 38

PARTICLE SHAPE PARAMETER VARIATION WITH EQUIVALENT PARTICLE DIAMETER

An auxiliary experiment was briefly conducted at NAFEC where a sample was obtained at the smoke number console for subsequent particle characterization. Two photomicrographs from this sample (cruise - 6/10/77) are shown in Figures 39 and 40 where the magnifications are 10,000X and 30,000X. The important result here is the difference in particle structure. The particles seem to have lost their long chain-like structures. This is probably due to a number of reasons including the long, small diameter sampling line. How the alteration influences the smoke number determination is unclear as well as the possible variation in particle alteration with different physical installations. However, the photomicrographs clearly demonstrate the effectiveness of the IITRI sampling system's ability to collect a representative particulate sample for characterization.

In reviewing the particle data obtained, the agreement in mean particle size by the methodologies employed indicate the acquisition of representative and reliable samples. This further supports the overall reliability of the sampling system in the characterization of aircraft engine exhaust particulate material.

3.3 System Operating Experience

Several comments are made in this section regarding the operational behavior of the sampling system. All the experience gained thus far results from the NAFEC testing.

The installation of the sampling system at NAFEC is shown in Figure 41. The sampling probe is immediately to the left connected to the flexible coupling. The diluter is at the center of the photograph supported by the wooden frame. The frame was specially made at NAFEC to position the diluter at the correct angle in order to mate properly at the fitting leading into the sound enclosure. Behind the sound enclosure

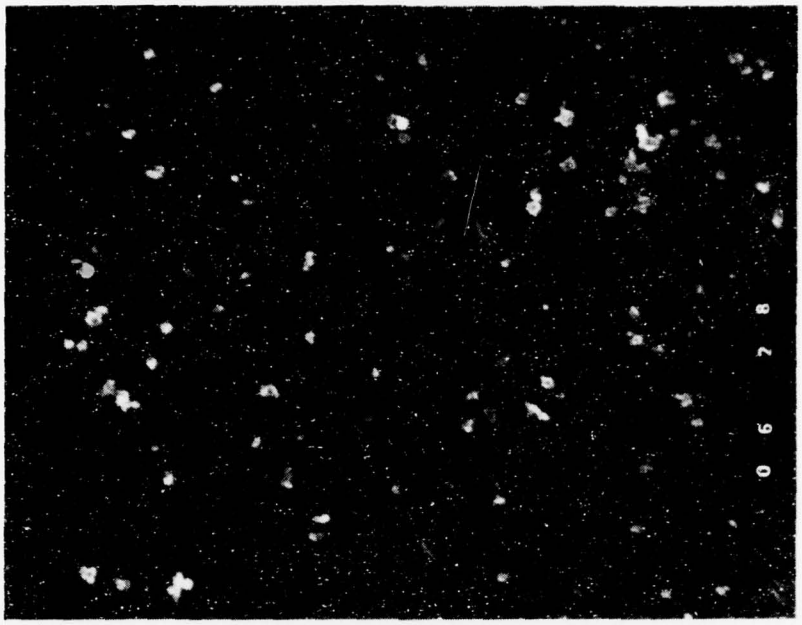

Figure 39

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES CAPTURED AT NAFEC'S SMOKE NUMBER CONSOLE (CRUISE - 6/10/77, MAGNIFICATION = 10,000X)

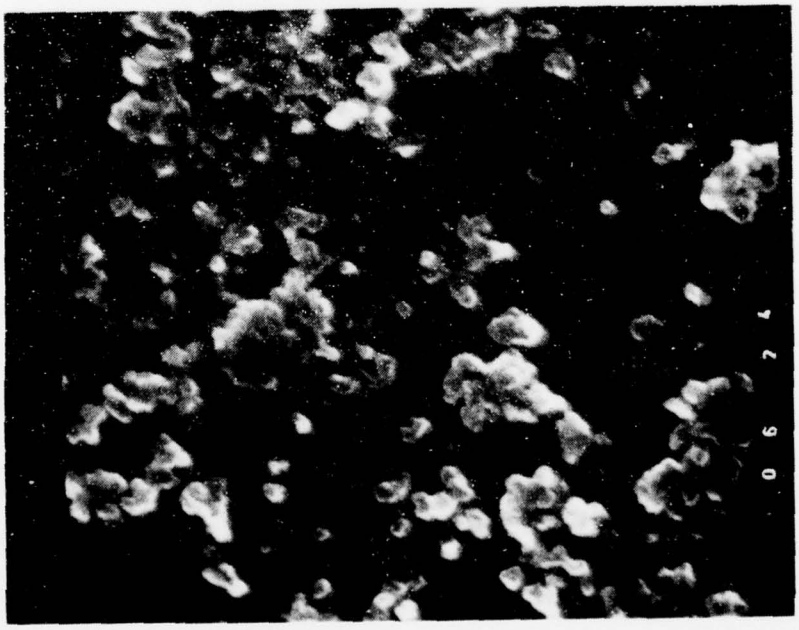

Figure 40

PHOTOMICROGRAPH OF TF-30 EXHAUST PARTICLES CAPTURED AT NAFEC'S SMOKE NUMBER CONSOLE (CRUISE - 6/10/77, MAGNIFICATION = 30,000X)

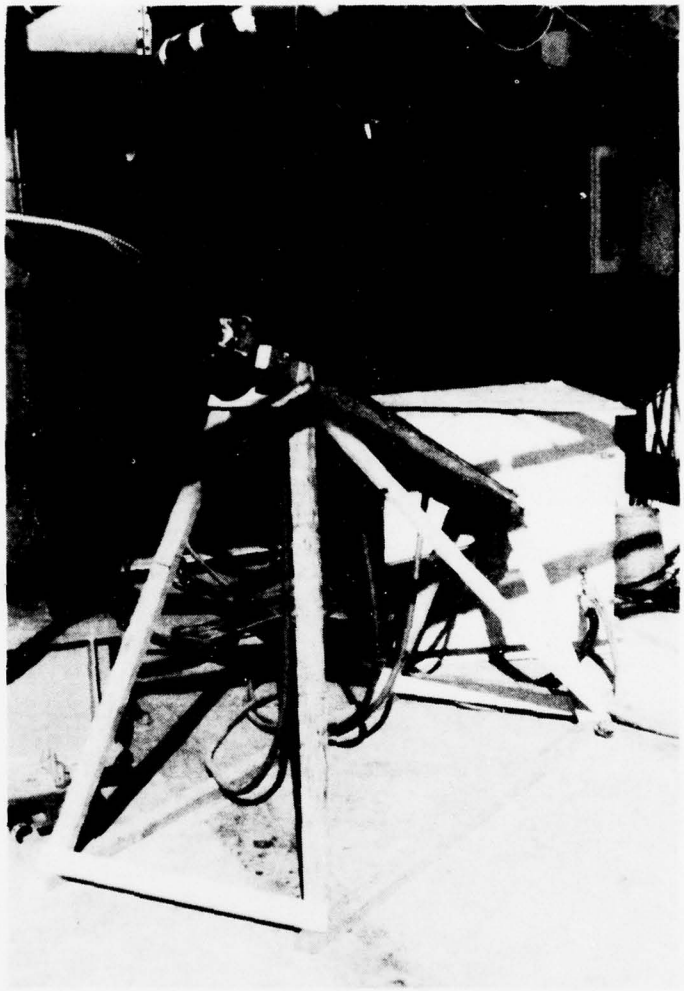

Figure 41

PHOTOGRAPH SHOWING INSTALLATION OF SAMPLING SYSTEM
AT THE NAFEC TEST CELL

is the air-processing unit. Figure 42 shows the sound enclosure itself with the front door removed and the outlet of the diluter at the left hand side of the photograph.

The sampling probe assembly incurred no visual damage in over 30 hours of engine operation time. Figure 43 is a photograph of the sampling probe installed on the engine at NAFEC. The sample flow from the probe was taken horizontally (middle right of photograph) to facilitate connection to the flexible coupling.

During the evaluation at NAFEC, the air supply pressure was inadvertently reduced to approximately 40 psig. At this pressure, the pneumatically driven assemblies would not operate. Not until the supply pressure was restored to approximately 60 psig did the pneumatic systems operate normally. Usually, the supply pressure is regulated to 80 psig to assure indexing.

The glass fiber filters effectively collected the incoming exhaust particles. During a preliminary experiment, two filters were installed -- a second to serve as back-up to the first. In all cases, the back-up filter collected an undeterminable weight gain although slight discoloration (grayness) was visible.

To demonstrate that the uniformity of the particulate deposit on the glass fiber filters, Figure 44 shows a photograph of the filters obtained in a preliminary test. These filters are shown because they occur over a fixed engine power condition (approach) where the total sampling time interval was varied. The uniformity in the gray tones across the filter face indicate a uniform deposit. In all the samples obtained, this characteristic was not violated.

The same uniformity in particle deposit was present on the EM grids. Counting the deposited particles over a given area on the grid surface at different locations (edges versus

Figure 42

PHOTOGRAPH SHOWING THE SOUND ENCLOSURE
AND THE INLET SAMPLE LINE

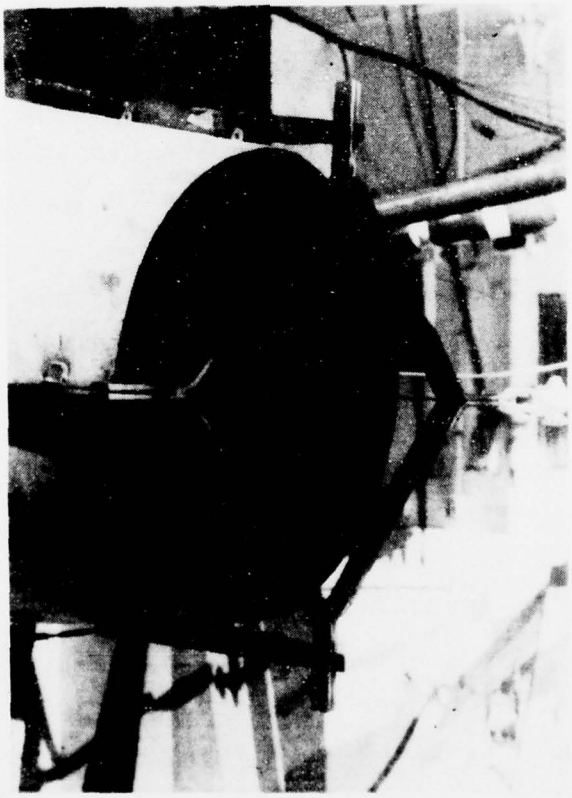

Figure 43

PHOTOGRAPH SHOWING INSTALLATION OF SAMPLING PROBE
ASSEMBLY AT NAFEC

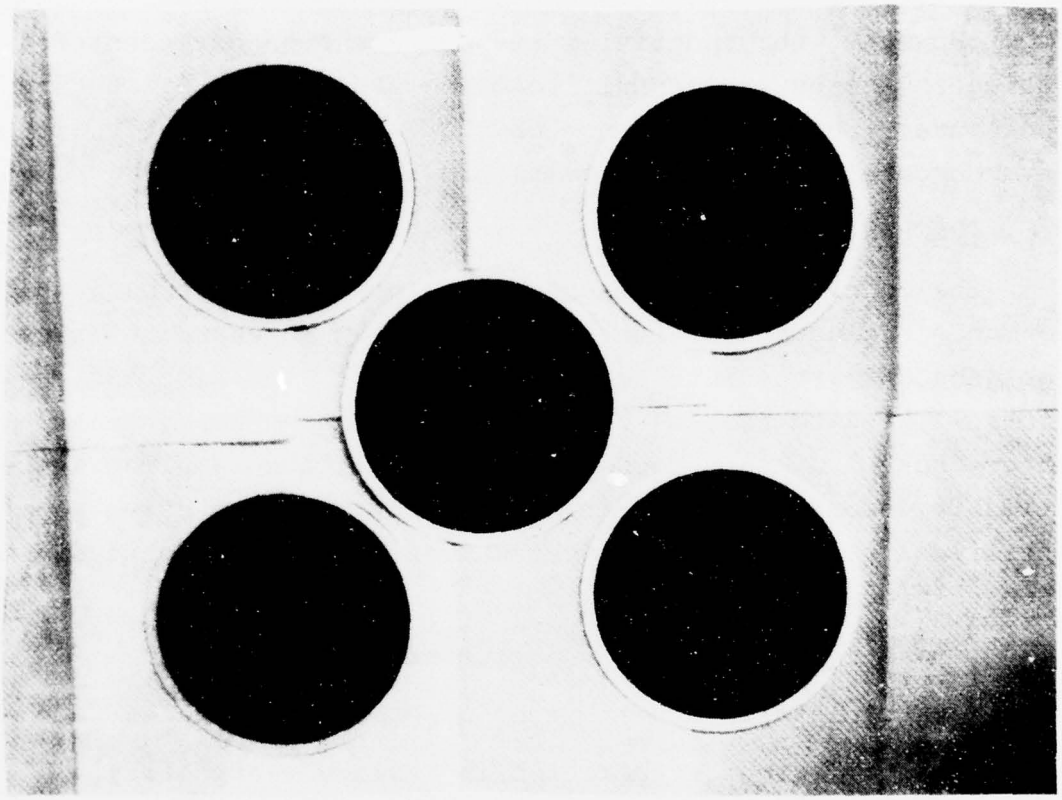

Figure 44

PHOTOGRAPH OF PRELIMINARY MASS-LOADING SAMPLES TAKEN OVER VARYING SAMPLE TIME INTERVALS AT APPROACH SHOWING UNIFORM PARTICULATE DEPOSITION

the center), no preferential particle deposition was observed. In addition, the same particle deposition "frequency" occurred on the grid wires themselves ruling out the possibility of local electrostatic effects modifying particle deposition.

As mentioned earlier, the EAA experienced repeated electronic failure. No consistent failure mode is apparent thus far. However, the underlying reasons are probably connected to inadequate environmental isolation as provided by the sound enclosure. For continued use of the EAA, substantially improved environmental isolation is being provided.

4. CONCLUSIONS

The conclusions pertinent to the program concern the performance evaluation of the sampling system in characterizing the exhaust particulate emissions from turbojet aircraft engines. The data base used for this evaluation was generated under Phase 2 of the program. In general, the sampling system reliably demonstrated the acquisition of representative samples. Specifically, the sampling system coupled with the analysis procedures generates the following:

- mass concentration of engine exhaust stream;
- particle size distribution of exhaust particles; and
- particle characterization in terms of morphology, shape, and elemental composition.

The discussion presented in Section 3 of this report develops and supports the above conclusions.

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1. Fenton, D.L., "Turbine Engine Particulate Emission Characterization", Phase 1 Report, Fed. Avia. Admin., Contract No. DOT-FA75WA-3722, IITRI Final Report No. C6352-10, Chicago, Ill., September 1976.

2. Aerospace Recommended Practice, ARP 1179, Smoke Measurement Techniques, Society of Automotive Engineers, Inc., 2 Pennsylvania Plaza, New York, N.Y. 10001, Issued May 4, 1970.

Appendix A

SCHEMATIC DIAGRAMS OF SAMPLER

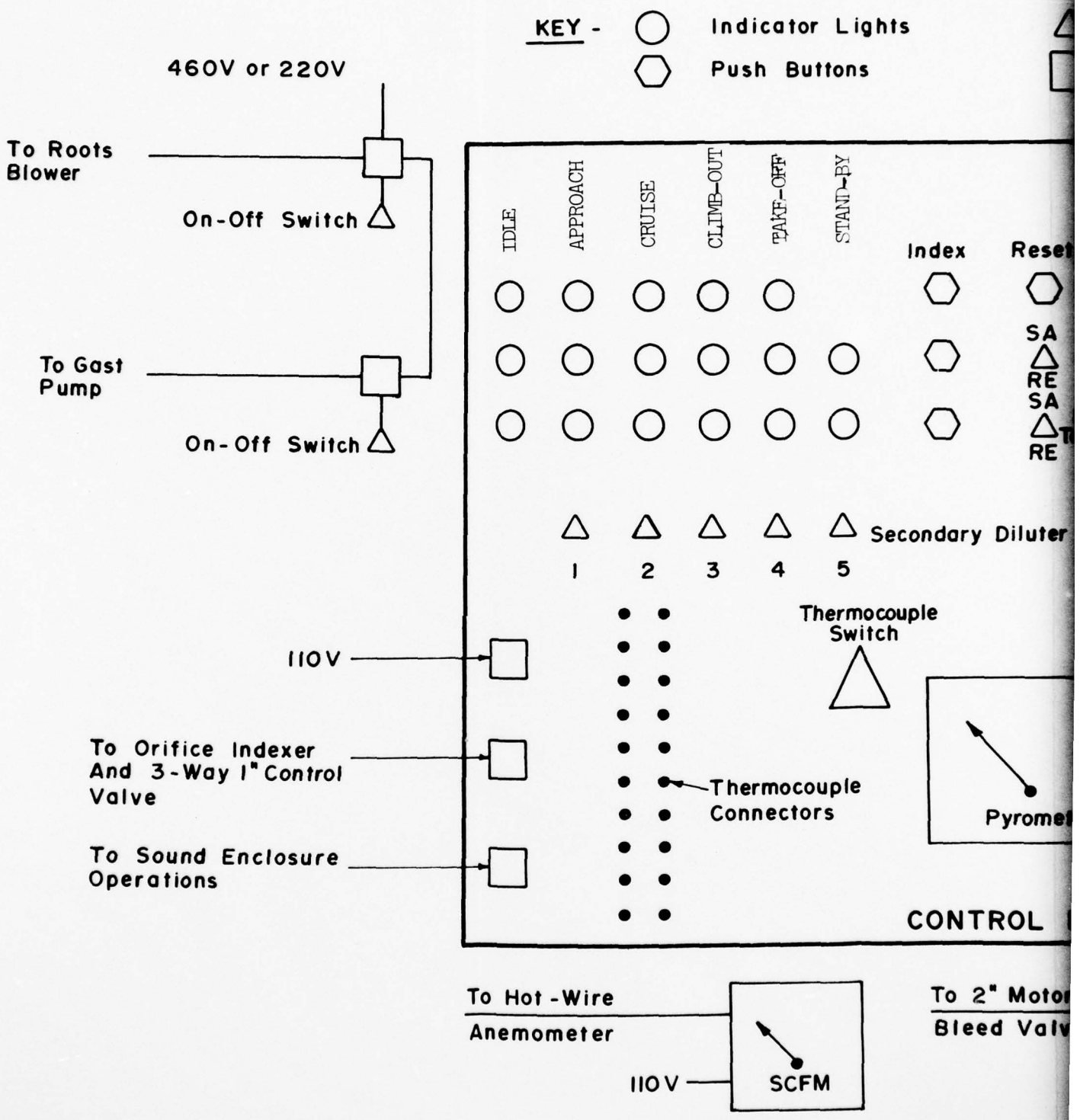

Figure A1

SCHEMATIC DIAGRAM OF THE CONTROL PANEL TO OPERATE THE E

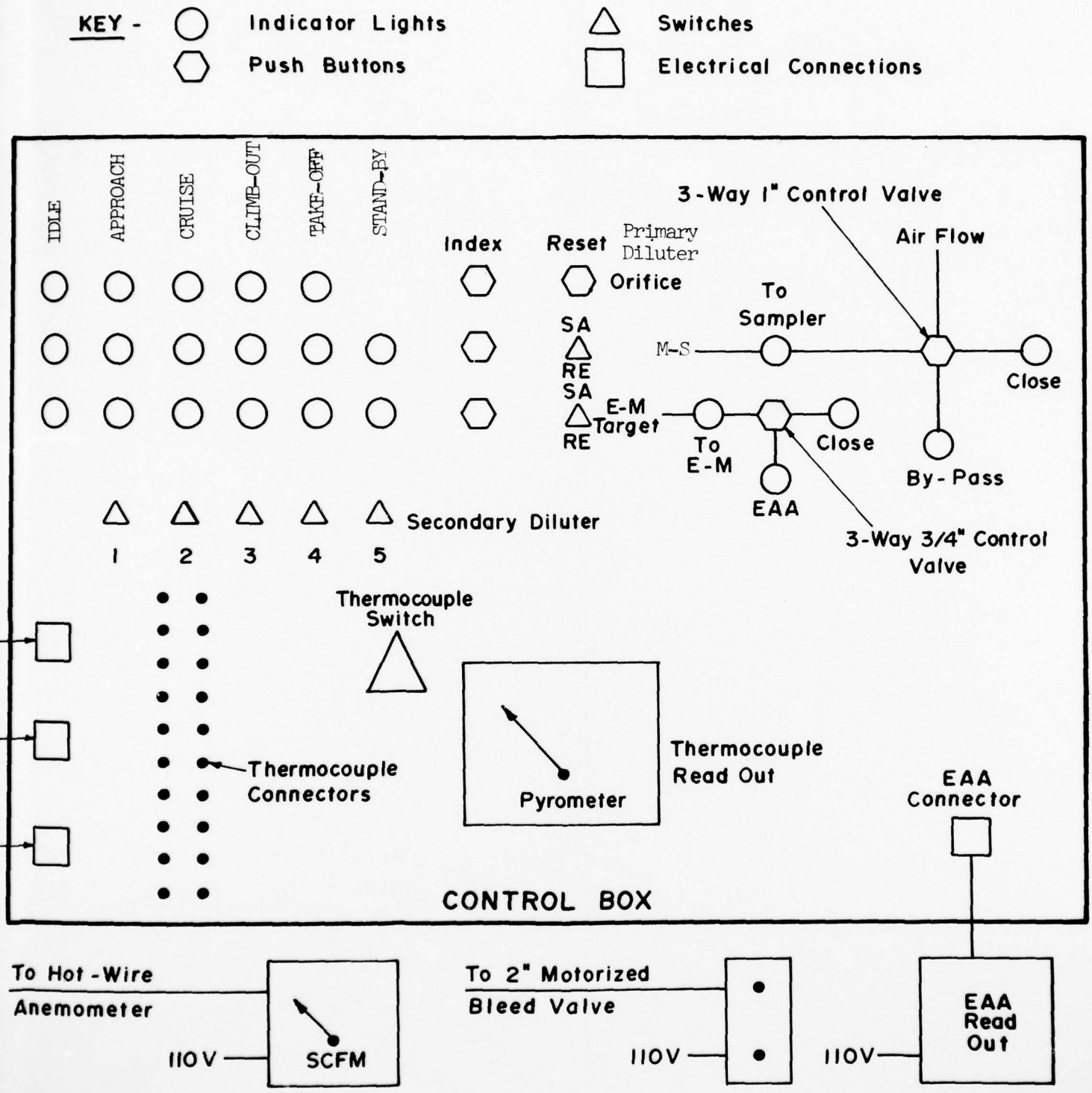

Figure A1

TIC DIAGRAM OF THE CONTROL PANEL TO OPERATE THE EXHAUST SAMPLER

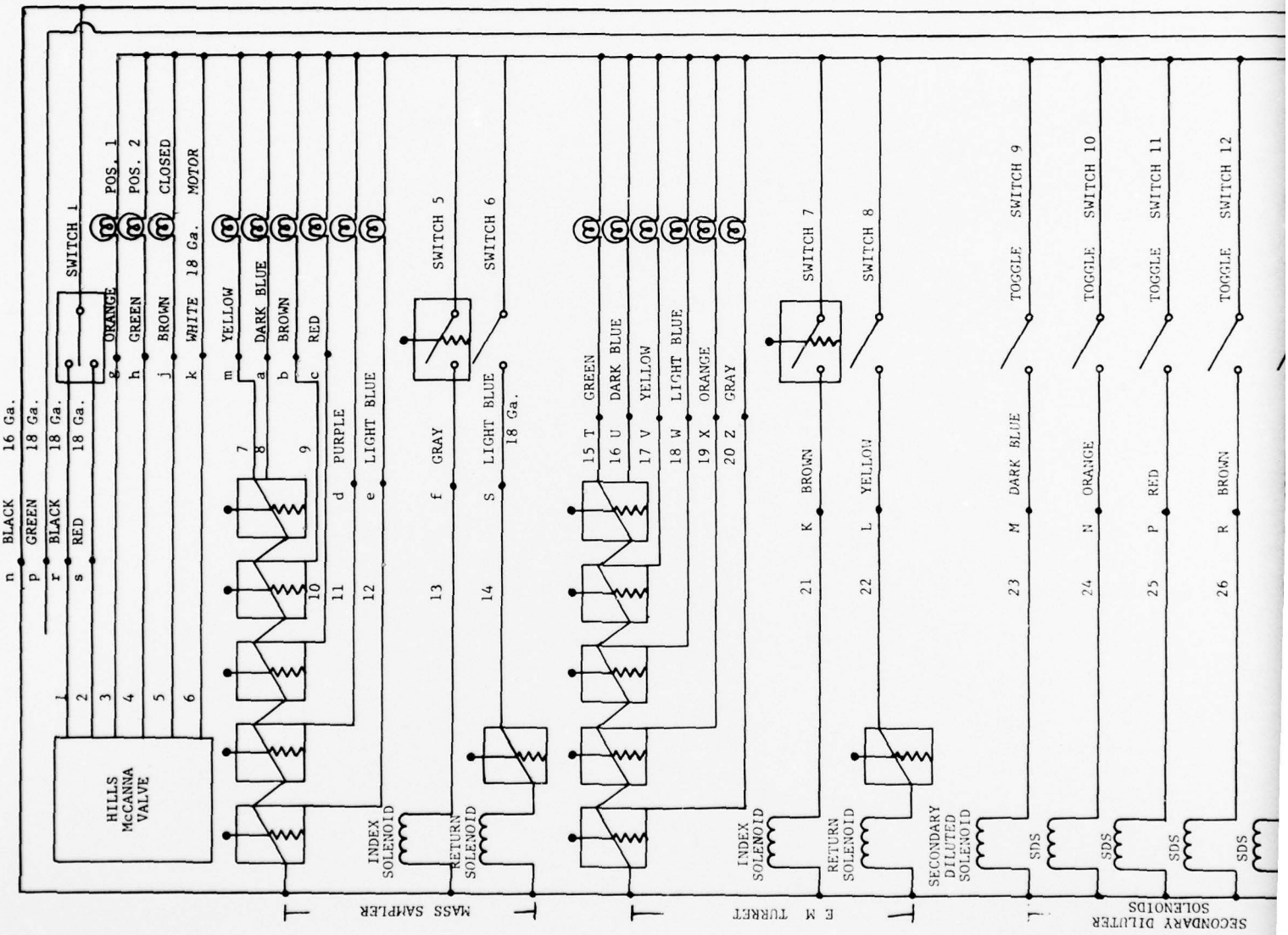

Figure A2

SCHEMATIC WIRING DIAGRAM OF JET ENGIN

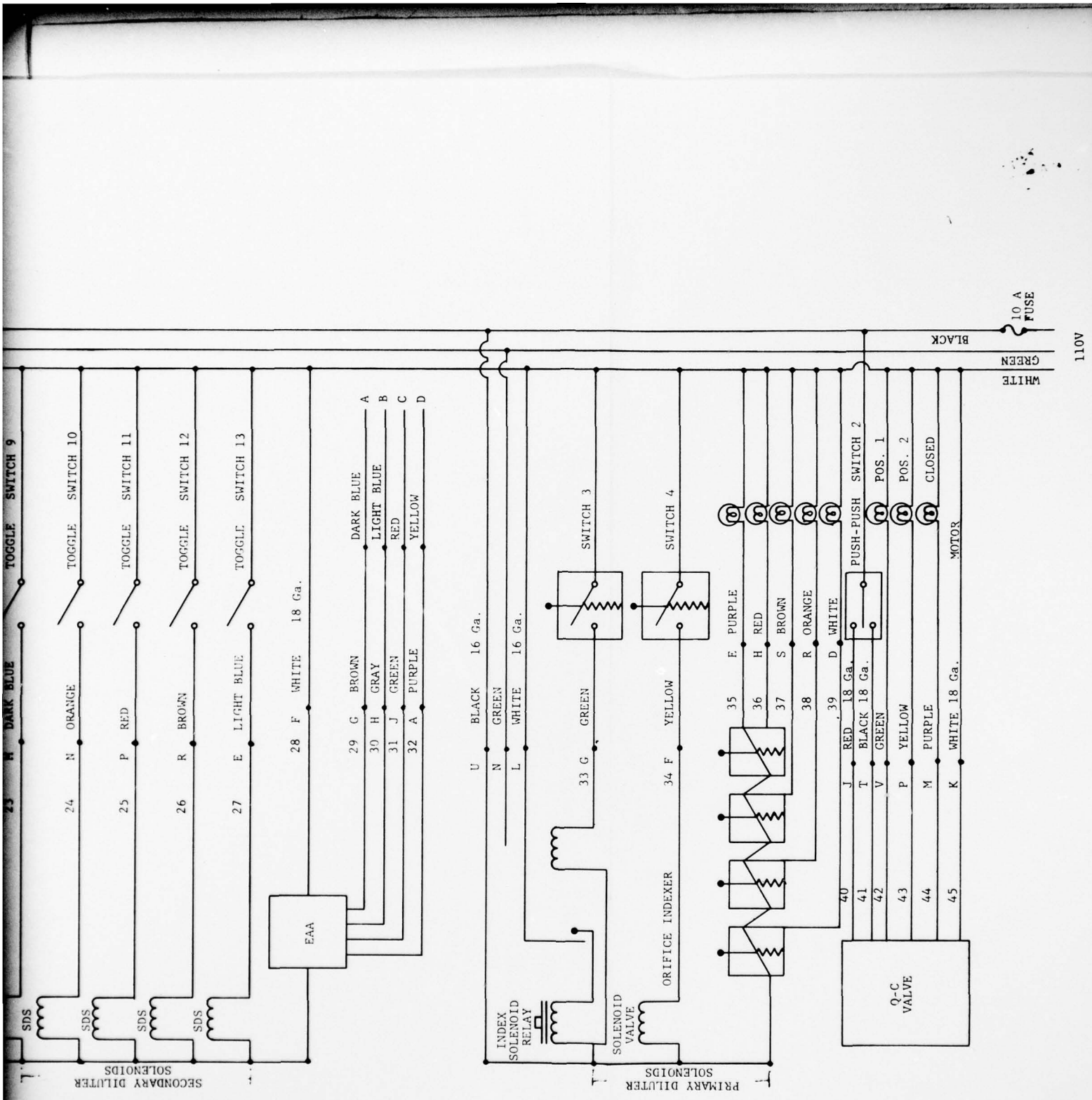

Figure A2

GRAM OF JET ENGINE EXHAUST SAMPLER

APPENDIX B

ACKNOWLEDGMENT

This document is the Phase 2 final report under Department of Transportation Contract No. DOT-FA75WA-3722 from the Federal Aviation Administration, entitled "Turbine Engine Particulate Emission Characterization". The report represents and discusses the design, operation, and performance of the exhaust particulate sampling system, designed by IITRI under this contract.

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